Challenges and opportunities of the integration of new consumers and decentralized power plants

By order of the Brazilian Energy Program of Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH and in cooperation with Agência Nacional de Energia Elétrica – ANEEL.

Main objective of this study is to inform about the current regulations, standards, as well as control and measurement methods of reactive power and power factor applied in Europe. Furthermore, the study describes interrelated challenges of and opportunities for the integration of new consumer groups and decentralized renewable energy based power generation.

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1 Introduction to reactive power

In direct current (DC) circuits voltage U and current I and power P are temporally constant and the power can be simply derived from $P = U \cdot I$.

In alternating current (AC) circuits voltage $u(t)$ and current $i(t)$ are time-dependent periodic functions, so that their product, the **instantaneous power** $p(t)$, is also time-dependent: $p(t) = u(t) \cdot i(t)$.

To compare AC power and DC power, the instantaneous power $p(t)$ is averaged over one period (with T as periodic time):

$$P = \frac{1}{T} \int_0^T p(t)\, dt$$

P is called the **active power** and is given in the unit Watt [W].

In the following AC voltage and current are assumed to be sinusoidal functions with a constant frequency f (50 Hz). The more general case, that voltage and current are not sinusoidal (e.g. because of mains feedbacks), will be discussed in chapter 5.5.1.

$$u = \hat{u} \cdot \sin(\omega t - \varphi_U) \quad \text{and} \quad i = \hat{i} \cdot \sin(\omega t - \varphi_I)$$

$\hat{u}$ and $\hat{i}$ are the amplitudes of voltage and current, $\omega = 2\pi f$ is the angular frequency and φ_U, φ_I are the phase shifts of voltage and current (see illustration 1.a).

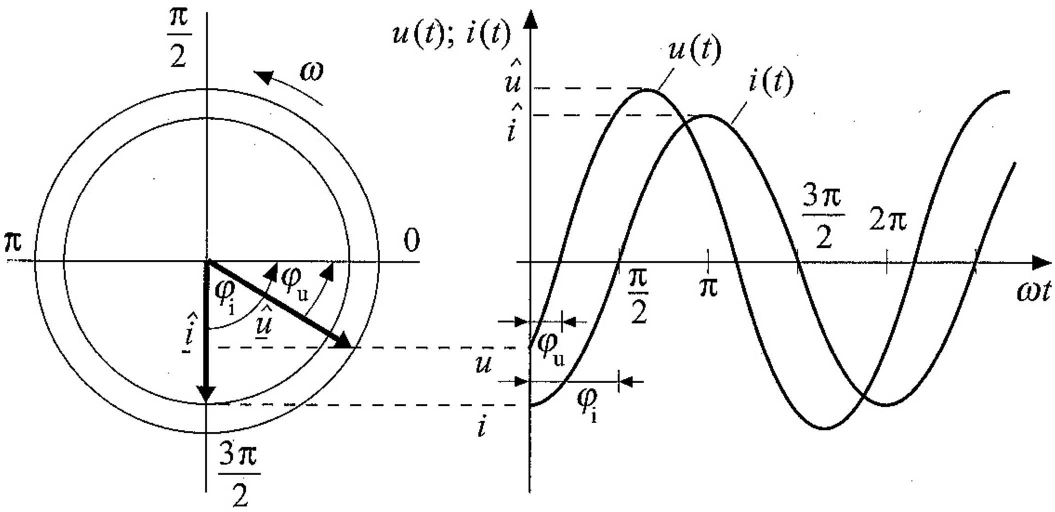


Illustration 1.a: Sinusoidal AC voltage and current shown in a vector diagram (left) and a line diagram (right) [Schlabbach 2008]

Calculating the instantaneous power $p(t)$ leads to the following equation:

$$p(t) = \hat{u}\,\hat{i}\cos(\omega t + \varphi_U)\cos(\omega t + \varphi_I) = \frac{\hat{u}\,\hat{i}}{2}\cos\varphi + \frac{\hat{u}\,\hat{i}}{2}\cos(2\omega t + \varphi) \quad \text{with} \quad \varphi = \varphi_U - \varphi_I$$

Using the rms-values $U = \hat{u}/\sqrt{2}$ and $I = \hat{i}/\sqrt{2}$ of voltage and current instead of the amplitudes it follows:

$$p(t) = UI\cos\varphi + UI\cos(2\omega t + \varphi)$$

The active power P is given by the average of the instantaneous power over one period (mean value):

$$P = \frac{1}{T}\int_0^T p(t)\,dt = UI\cos\varphi$$

This means, that the active power P in a AC circuit is reduced by the so-called **power factor** $\lambda = \cos\varphi$. φ is the phase shift between voltage and current. The instantaneous power $p(t)$ oscillates with doubled frequency and amplitude UI about the mean value $P = UI\cos\varphi$ (see illustration 1.b).

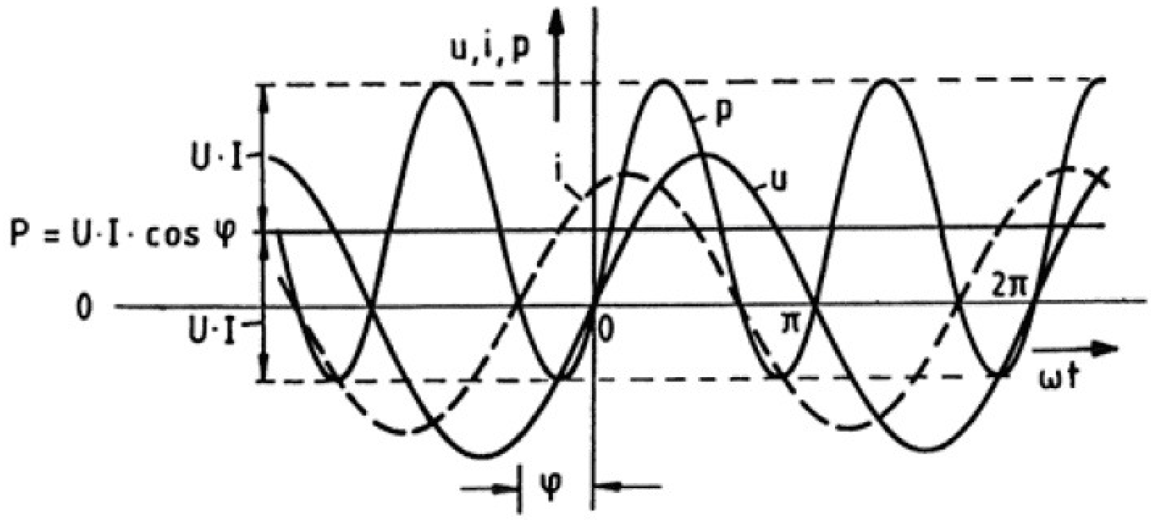


Illustration 1.b: Voltage, current and instantaneous power [Weißgerber 2007]

The product UI of the rms-values of voltage and current is called **apparent power** S and specifies the maximum possible active power for a phase shift $\varphi = 0$ $(\cos\varphi = 1)$. The apparent power is given in the unit volt-ampere [VA].

The instantaneous power can also be expressed as a superposition of two sinusoidal components having a phase shift of 90°:

$$\begin{aligned} p(t) &= UI\cos\varphi + UI\cos(2\omega t + \varphi) \\ &= P + S\cos(2\omega t + \varphi) \\ &= P + S\cos 2\omega t\cos\varphi - S\sin 2\omega t\sin\varphi \\ &= P + P\cos 2\omega t - S\sin\varphi\sin 2\omega t \\ &= P(1 + \cos 2\omega t) - Q\sin 2\omega t \qquad \text{with} \qquad Q = S\sin\varphi \end{aligned}$$

$Q = S\sin\varphi$ is called **reactive power** and given in the unit volt-ampere reactive [var]. The reactive power is positive in the case of an inductance ($\varphi > 0$) and negative in the case of a capacitance ($\varphi < 0$), but the mean value of the reactive component $Q\sin 2\omega t$ of the instantaneous power is zero. Therefore Q is not a mean value like the active power P, it is the amplitude of the power component, which oscillates between the energy source and a capacitive or inductive load.

In the following you find a summary of the definitions made in this chapter:

- **Apparent Power**: $S = U\,I$
- **Active Power**: $P = S\cos\varphi$
- **Reactive Power**: $Q = S\sin\varphi$
- **Power Factor**: $\lambda = \cos\varphi = \dfrac{P}{S}$

In general there exists the following interrelationship between the active, reactive and apparent power:

$$S^2 = P^2 + Q^2$$

Therefore an unknown power can be derived when the two others are known.

1.1 Need and (today's) provision of reactive power for electricity consumers

1.1.1 Need for reactive power of electricity consumers

Active power with the unit Watt [W] is well known and understood even among non experts. To operate electricity consumers a certain amount of active power is required. As soon as an electricity consumer is not a pure resistive load – and voltage and current are not any longer in phase – the electricity consumer has a demand for reactive power [var]. Many or most electricity consumers contain elements that consume reactive power. In the following some examples are given.

Transformers, induction generators and inductive switching devices for e.g. fluorescent and energy saving lamps require a magnetizing current for the development of the magnetic flux. Those currents are of pure inductive nature.

Small and medium sized induction generators are used in large quantities in household appliances as well as in drives and actuators in industry. Illustration 1.1.1.a shows the characteristics of a low voltage induction motor with short circuit rotor. Even in no load condition reactive power has a share of app. 35 % of the rated apparent power. Whereas $\cos\varphi$ at rated power is above 0.8 – under part load condition it is much lower reaching 0.1 with no load.

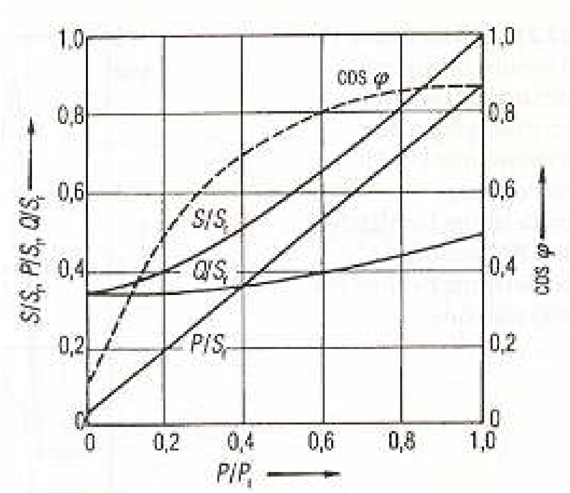


Illustration 1.1.1.a: Characteristics of a low voltage induction generator with short circuit rotor [Oeding 2004].

An extreme example from industry is electric arc furnaces. Illustration 1.1.1.b shows a typical characteristic in relation to the maximum furnace current. The amount of

reactive power is in the same range like active power when the latter is at its maximum. Therefore $\cos\varphi$ is 0.7. During the melting process $\cos\varphi$ is in between 0.5 to 0.7.

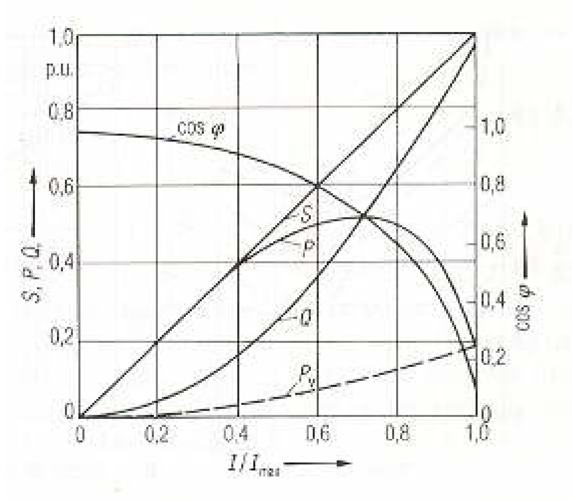


Illustration 1.1.1.b: Characteristics of an electric arc furnace [Oeding 2004].

1.1.2 Provision / Compensation of reactive power of electricity consumers

The requirement for reactive power does not lead to higher power consumption at the consumer side. The electricity meter and therefore the electricity bill is not affected by the consumption of reactive power. A pure reactive load causes an electric current that one half period is going in direction to the consumer and the other half period from the consumer towards the grid.

But as the current is real – independent of its direction – it has to be transmitted via the grid lines. And that means investment costs in line capacity and additional transmission losses on the lines. The costs occur at the side of the grid operator. To keep losses as small as possible reactive power should be supplied / compensated at the place of its requirement.

With certain customer's consumer characteristics reactive power consumption can easily reach 30 % or more of active power share. As a consequence utilities / grid operators install reactive power meters and bill the consumption of reactive power. Alternatively – to save this cost – customers can operate power factor correction facilities. With those facilities the allocation of reactive power is possible without loading the grid infrastructure with reactive currents.

In practice power characteristics are of inductive nature. As a consequence compensation of reactive power at the consumer site is done by the installation of capacitors (Illustration 1.1.2.a).

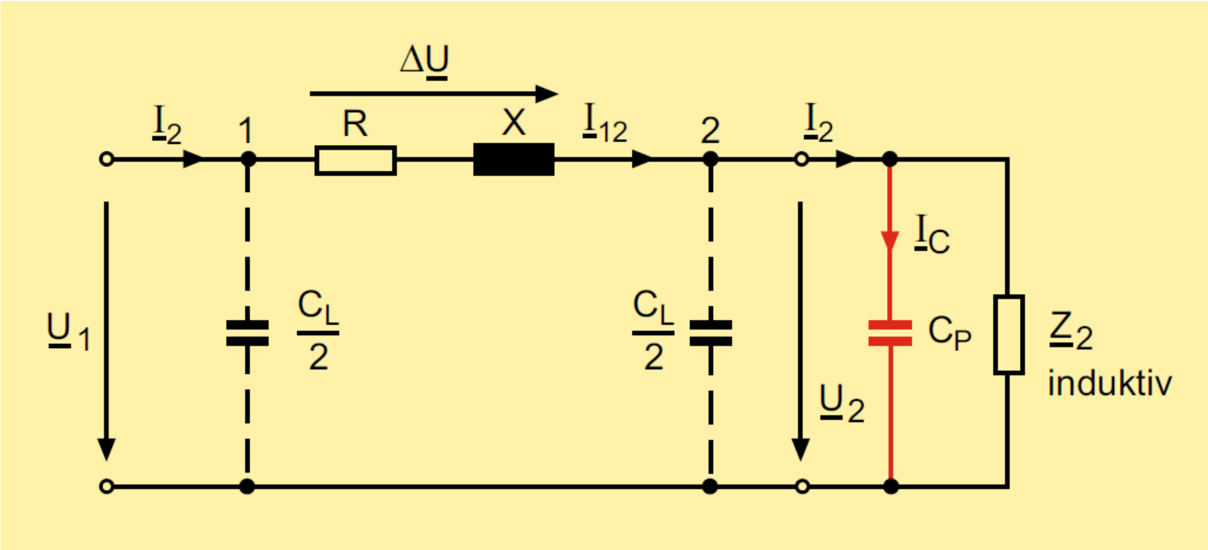


Illustration 1.1.2.a: Parallel compensation of consumers with inductive behavior (U_1 Voltage at the beginning of a line, U_2 Voltage at the end of a line, C_L Grid capacity, C_P Capacitor for reactive power compensation, Z_2 inductive load) [Schwab 2009]

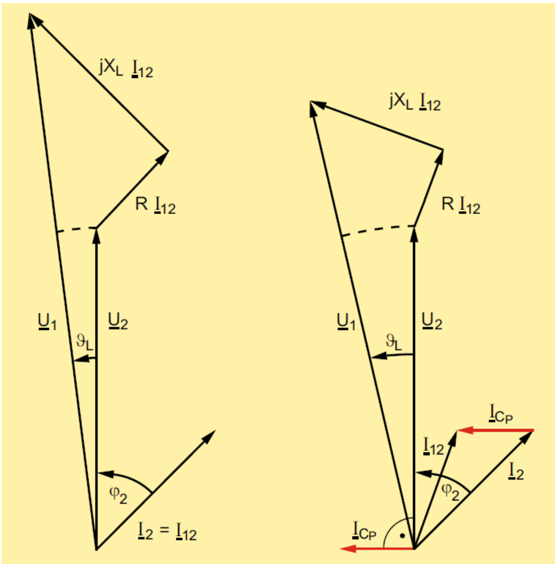


Illustration 1.1.2.b: Vector diagram of a line with ohmic-inductive load with (left) and without (right) compensation by capacitors

The consequence of the compensation can be seen in illustration 1.1.2.b. On the one hand φ is decreased and therefore $\cos\varphi$ is increased with a decreased overall current. On the other hand the voltage drop on the line is decreased, too. A further consequence is an increase of the line angle υ_L. In high voltage lines that decreases stability and therefore this way of compensation is not used there.

As the compensation capacity is load dependent and the load normally is changing capacitors are switched on and off according to the load situation.

In grids with a high share of electronic converters harmonics play an important role that could lead to high currents by resonant circuits with transformer reactance.

Therefore absorption circuits are installed to avoid problems (see chapter 5 about EMC).

1.2 Need and (today's) provision of reactive power for grid infrastructure

1.2.1 Need for reactive power of grid infrastructure

Electricity supply systems consist of numerous elements in order to transmit and distribute the electric power generated in power stations to the electricity consumers. According to distances and power levels different voltage levels are applied to parts of the grid. One distinguishes high voltage, medium voltage and low voltage grids.

Grids of different voltage levels are interconnected via transformers that provide an inductive coupling of the different grids. Those transformers have a high demand on inductive reactive power.

The grid lines and cables themselves have a reactive power demand themselves. Whereas the line itself is of pure ohmic behavior, in operation the lines show both capacitive and inductive behavior. The conductor loop from forth and back line or earth, respectively, are linked with a magnetic flow that behaves like an inductor. The voltage between forth and back line or the earth, respectively, establish an electrical field that behaves like a capacitor.

Overhead lines with both capacitors and inductors the reactive power need depends on the relation of transmitted power towards the natural power P_{nat} [1] of the line. In lines with a rated voltage of up to 110 kV and relatively short line lengths normally the transmitted apparent power is above natural power and the line has inductive behavior. In low load situations the transmitted power is below natural power and the line shows capacitive behavior. In case the transmitted apparent power is equal to the natural power no reactive power has to be transmitted. Illustration 1.2.1.a shows the capacitive and inductive behavior of transmission lines of different voltage levels.

[1] Natural power is transmitted when a line is charged with its characteristic wave impedance $Z_0 = \sqrt{L'/C'}$, with L' inductance per unit length and C' capacity per unit length.

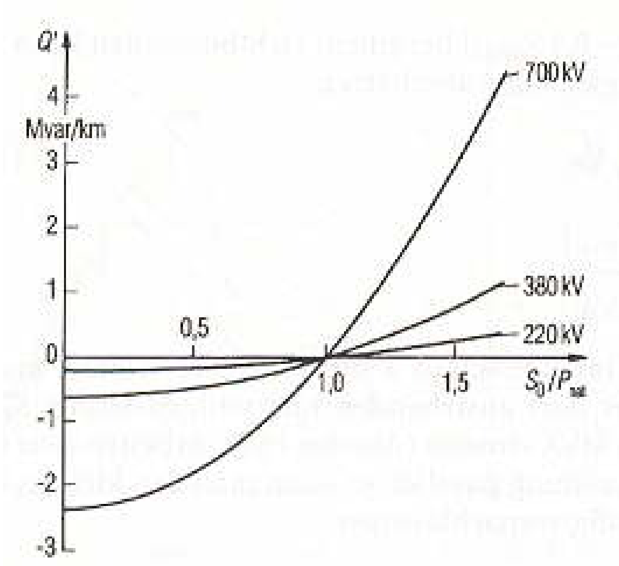


Illustration 1.2.1.a: Reactive power demand Q' per kilometer line depending on the transmitted apparent power $S_{ü}$ related to natural power P_{nat} with a line length of 100 km [Oeding 2004].

1.2.2 Provision / Compensation of reactive power for grid infrastructure

Reactive power provision by synchronous generators

Traditionally, electric power generation is done in centralized large scale power stations that feed to the grid at highest voltage level. Independent from the primary energy – whether it is hydro power, brown coal, hard coal, natural gas or nuclear power – the conversion of mechanical power from turbines into electrical power is done with synchronous generators.

Synchronous generators are capable of both provision of active and reactive power. In integrated networks with hundreds or even thousands of different power stations hundreds or thousands of synchronous generators form the grid voltage and the grid frequency.

From the perspective of a single synchronous generator the grid is rigid. That means in first approximation that an increased driving torque does not lead to an increased speed of the generator or to an increased grid frequency but to an increased polar wheel angle and therefore to an increased active power generation.

In a similar way a single synchronous power station is not able to change the grid voltage significantly but an increased exciting current result in an increased reactive power supply as is shown in illustration 1.2.2.a.

As even interconnected grids are not completely rigid an increase of active power consumption leads according to a decreasing speed / active power characteristics to a slightly decreased grid frequency. An increased reactive power consumption leads

according to a decreasing voltage / reactive power characteristic to a decreased voltage at the generator's place.

Therefore, in an interconnected operation mode one obtains a "frequency – active power control" and a "voltage – reactive power control".

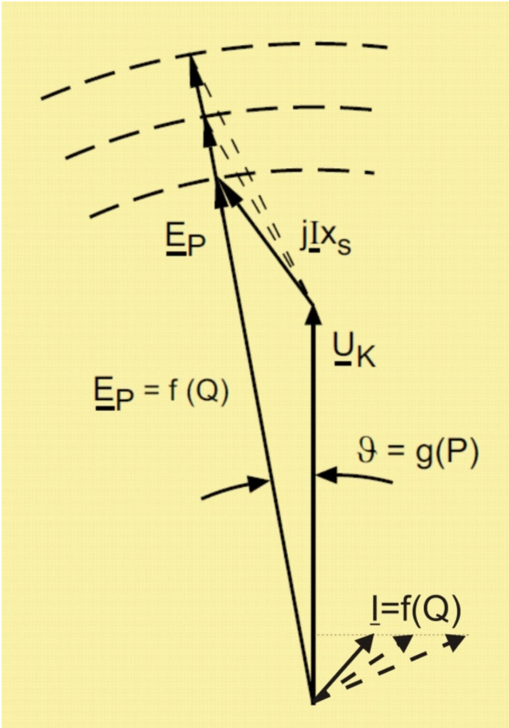


Illustration 1.2.2.a: Control of reactive power generation with synchronous generators by changing the exciting current and therefore the polar wheel voltage.

A big part of the required reactive power within grids is supplied by synchronous generators that are driven by steam and hydro power stations. Synchronous generators that are operated in phase shifter mode are only of minor importance. Capacitors and Flexible AC Transmission Systems (FACTS) play an increasing role in the provision of reactive power.

Turbo-generators are capable to provide reactive power at low cost, especially when they operate at $\cos\varphi$ close to 1. Besides increasing costs with decreasing power factor also increasing losses within the generator and therefore decreased efficiencies are occurring when reactive power is provided by synchronous generators. From a cost perspective the provision of reactive power between $\cos\varphi = 1..0.9$ synchronous generators is the best option. Capacitors and impedances have lower losses (losses with synchronous generators in $W/_{k\,\text{var}}$ are 50 % to 100 % higher than losses with capacitors [Oeding 2004]). Both in relation to cost and losses in phase shifter mode are worst. The advantage of that operation is the dynamic voltage control ability in high voltage transmission systems.

Reactive power compensation in interconnected grids

The voltage difference between nodes of a high voltage grid are resulting mainly from reactive currents (L>>R). Minimization of reactive currents and therefore maintaining the voltage in the grid nodes close to the rated voltage is the responsibility of grid operators. They aim at having a $\cos\varphi$ close to 1. With the minimization of the reactive power flow also line losses are minimized. Therefore, a consistent voltage profile and low line losses follow the same target. To do so it is important to compensate reactive power at the place of occurrence.

With long high voltage lines that are highly loaded the line inductance plays the dominant role. It causes high inductive voltage drops along the line. For keeping the rated voltage at the end of the line and for an increase of the transmission capacity the stability increasing serial compensation is applied. By serial connection of a capacitor or a capacitor bank in the line the impact of the line inductance can be compensated and therefore the voltage drop be decreased. The line then can be operated close to its natural power (illustration 1.2.2.b).

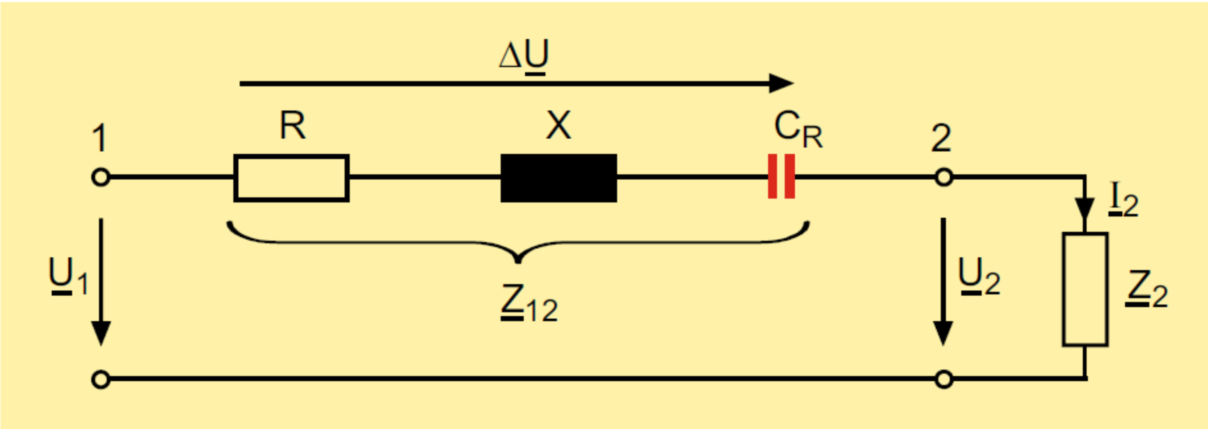


Illustration 1.2.2.b: Serial compensation in order to keep losses low and the voltage almost constant [Schwab 2009].

Illustration 1.2.2.c shows the effect of serial compensation. Depending on the size of capacitor C the relation between $\underline{U}_1$ and $\underline{U}_2$ as well as the amount of the line angle ϑ can be influenced. In high voltage grids with shorter distances a constant voltage is of main importance and the capacitor will be selected in a way that the magnitude of the voltages will be in the same range. In highest voltage systems and long distance transmission stability plays the more important role and the capacitor C will be selected in order to make the line angle almost zero.

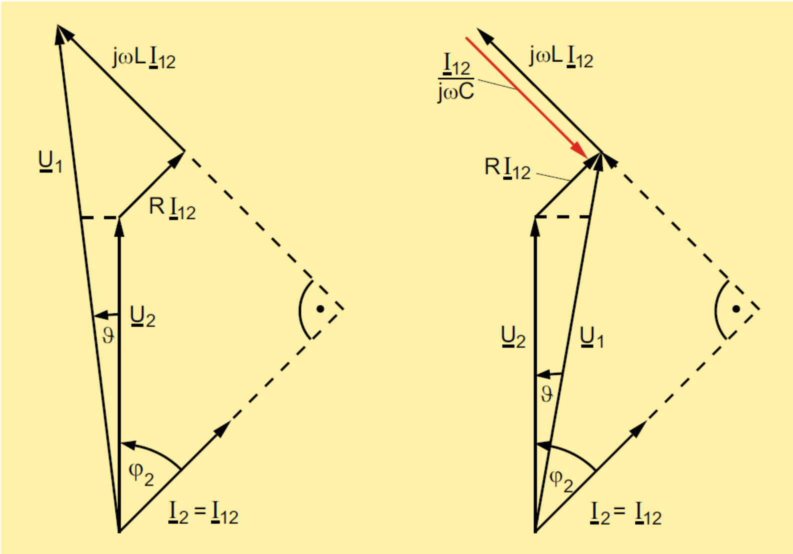


Illustration 1.2.2.c: Vector diagram with and without serial compensation [Schwab 2009]

In high voltage systems at low load or no load the line has capacitive behavior. Resulting from capacitive charging power high voltages at the line end and stability problems can occur. Parallel inductors (illustration 1.2.2.d) can avoid this effect. Illustration 1.2.2.e shows that parallel inductors can decrease both voltage superelevations and line angle.

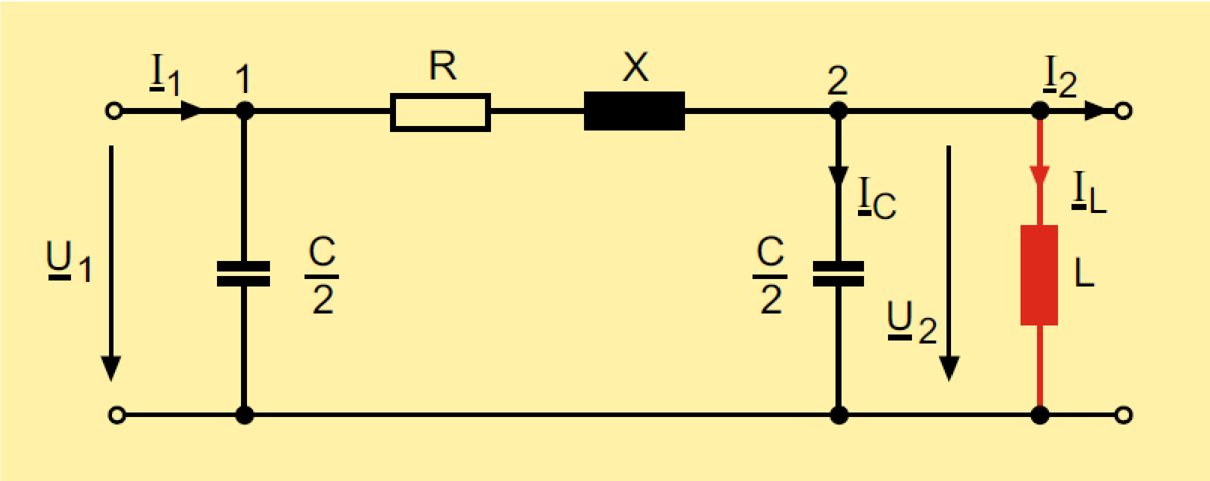


Illustration 1.2.2.d: Inductive parallel compensation of low or no loaded lines [Schwab 2009]

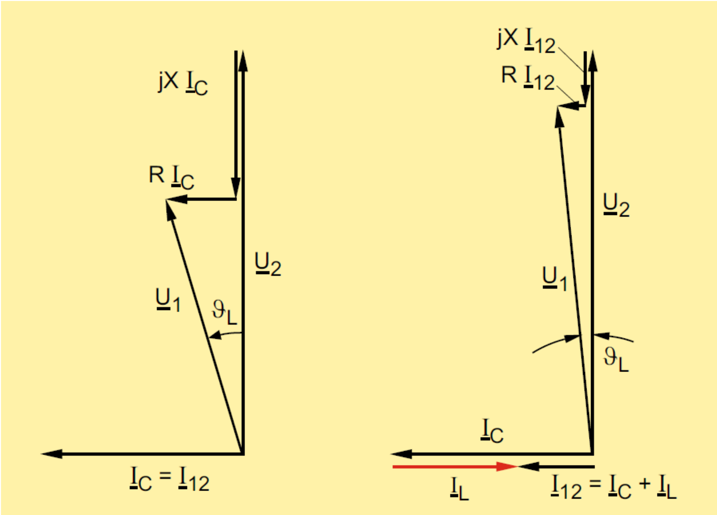


Illustration 1.2.2.e: Vector diagram of a line in no-load operation without and with inductive parallel compensation [Schwab 2009]

Illustration 1.2.2.f shows as an example the 750 kV power transmission between the hydro power station of Itaipu and the region of São Paulo with all discussed compensation methods: parallel inductances, serial capacitors, synchronous generators in phase shifting operation as well as parallel capacitors for reactive power compensation.

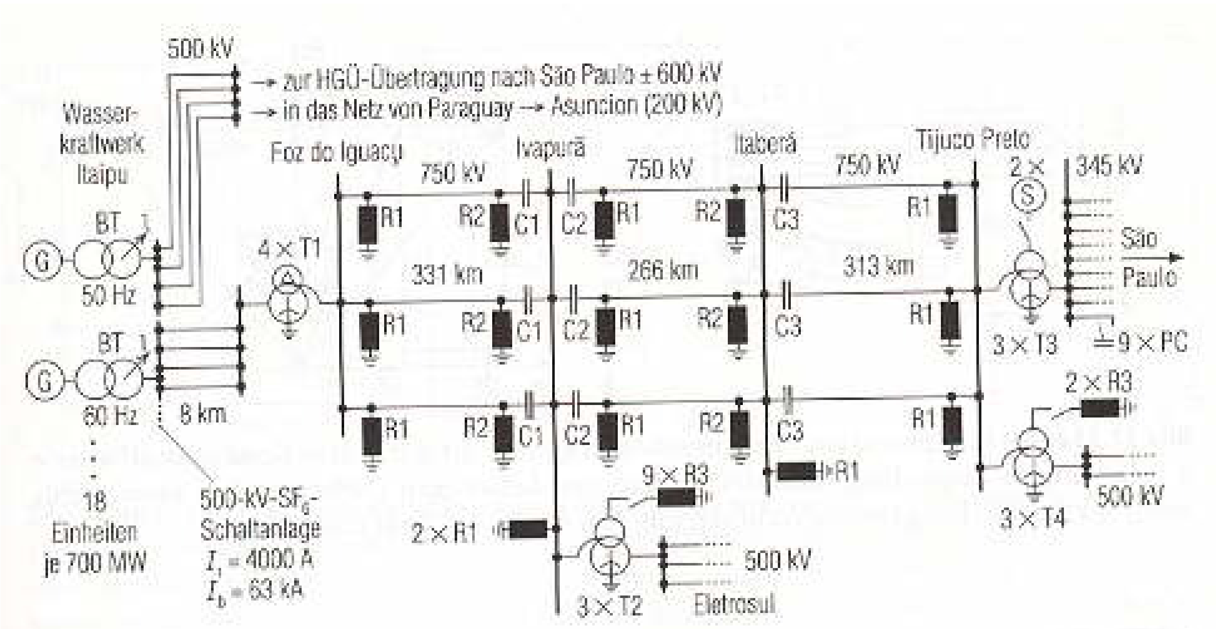


Illustration 1.2.2.f: Reactive power compensation of the 750 kV power transmission line between Itaipu and Sao Pãulo [Oeding 2004]

2 Standards and responsibilities for the definition of power factors in different voltage levels

Since July 2009 the control of the European high voltage transmission grid is centralized in the European Network of Transmission System Operators for Electricity (**ENTSO-E**). The work of the following former associations has been fully integrated into ENTSO-E:

- **ATSOI** - Association of the Transmission System Operators of Ireland
- **BALTSO** - Baltic Transmission System Operators
- **ETSO** - European Transmission System Operators
- **NORDEL** - Nordic Transmission System Operators
- **UCTE** - Union for the Coordination of the Transmission of Electricity
- **UKTSOA** - UK Transmission System Operators Association

The ENTSO-E includes 42 transmission system operators (TSOs) from 34 countries (see illustration 2.a). The TSOs are responsible for the bulk transmission of electric power on the main high voltage electric grid. TSOs provide grid access to the electricity market players (i.e. generating companies, traders, suppliers, distributors and directly connected customers). In order to ensure the security of supply, they also guarantee the safe operation and maintenance of the system. In many countries, TSOs are in charge of the development of the grid infrastructure, too [ENTSOE 2009].

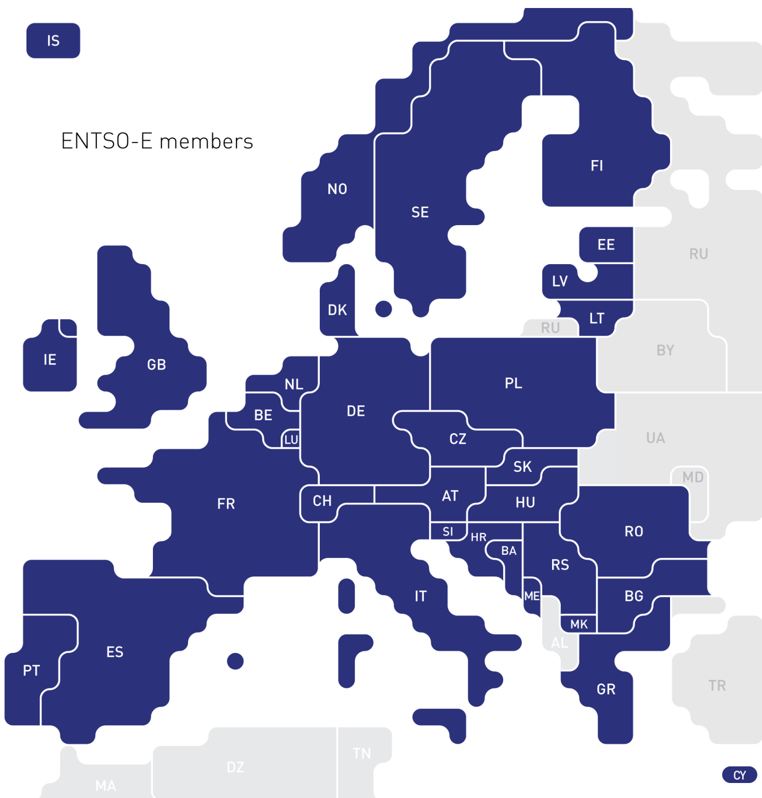


Illustration 2.a: Members of the ENTSO-E [ENTSOE 2009].

The activities of ENTSO-E are organized in the three committees for system development, system operations and market. The activities are focused on [ENTSOE 2009]:

- reliable operation and optimal management,
- technical evolution of the European transmission grid,
- security of supply,
- network development statements,
- promotion of relevant R&D and the public acceptability of transmission infrastructure,
- consultation with stakeholders and positions towards energy policy issues.

2.1 Regulation of power factor in high-voltage grids

UCTE Operation Handbook

The TSOs are responsible for the bulk transmission of electric power on their high voltage electric grid and provide grid access to the electricity market players. In order to ensure the security of supply, they also guarantee the safe operation and maintenance of the system. In this frame they are responsible for the voltage control in their grid, which is directly connected to the reactive power situation at the grid nodes.

In Germany there are four TSOs, which are responsible for different parts of the German high voltage grid:

- EnBW Transportnetze AG
- transpower stromübertragungs gmbh
- Amprion
- Vattenfall Europe Transmission GmbH

The regulations of the former association of the transmission system operators are still valid and published in [ENTSOE 2009]. The main document is the “UCTE Operation Handbook” (final version from 19 March 2009), which is a collection of operation principles and rules for the transmission system operators in continental Europe [OH 2009].

Every TSO in the UCTE network has declared to follow the technical standards and procedures that are comprised in the UCTE Operation Handbook. This Operation Handbook therefore serves as the reference (“legislation”) for the grid operation by the TSOs and guarantees the UCTE’s quality and reliability standards. The Operation Handbook sets also standards for the essential requirements and capabilities for every party operating a generating unit in the UCTE interconnected network [OH 2009].

Concerning reactive power mainly the policy P3 “Operational Security”, part B “Voltage control and reactive power management” is in force. But there are no values or limits given for the amount of reactive power or the power factor, only general recommendations to limit reactive power. In the following a short summary and extract of the main aspects of the policy P3 part B is given [OH 2009]:

General

Depending on their operational state, all generators, loads and system components (lines, cables, transformers) are either reactive power consumers or producers. To compensate for an excessive consumption of reactive power, TSOs have to make sure that efficient producers feed sufficient reactive power into the networks. As the transmission of reactive power causes voltage drops, the reactive power generation and consumption have to be situated as close to each other as possible to obtain an acceptable voltage level at each grid node. This reactive power can be produced in the responsible area of the TSO or in those of adjacent TSOs. In this last case, specific bilateral agreements should be made to transfer reactive power through tie-lines. Voltage control is thus primarily a regional problem, which may involve several TSOs.

Responsibilities and standards

Each TSO is responsible for managing voltage and reactive power in its own network. TSOs are also in charge of coordinating all needed operational actions with their adjacent TSOs and other stakeholders owning installations connected to the transmission network (distribution system operators and related distribution networks, connected generating units, connected consumers).

TSOs are committed to have available a sufficient reserve of rapid reactive power resources participating to the primary voltage control in order (i) to ensure normal operational conditions with a continuous evolving of load and transits and (ii) to prevent voltage collapse after any contingency.

Additionally TSOs have to keep available a sufficient number of other reactive power sources like generators, capacitors and reactors connected to the grid, which contribute to reactive power generation or absorption, in order to maintain or get back the voltage in normal ranges after any contingency.

Each TSO must have information of the main reactive power resources available for use in the transmission network of its own responsible area. Adjacent TSOs shall be duly informed without delay about restriction of reactive power sources.

Extensive reactive power flows beyond the own consumption of the tie-lines are the result of the different voltage levels on each side of the boundary. In order to ensure a safe operation of the synchronous area, adjacent TSOs shall agree on common voltage ranges on each side of the border to ensure the continuous voltage control.

A co-ordination between adjacent TSOs is needed in order to manage voltage control and reactive power resources near boundary preventing, that individual actions have a contrary effect to the security of neighbors in normal operation and in case of disturbances.

The appendix A3 “Operational Security” of the UCTE Operation Handbook gives some further general rules for voltage regulation regarding the following issues [OH 2009]:

Sizing of the equipment

Too high voltage can lead to accelerated ageing or destruction of the equipment. Generally, the upper limit is around 420 kV for the 380 – 400 kV network and around 245 kV for the 220 – 225 kV network. Exceeding can be acceptable but for a limited time duration only. For example, a voltage between 420 kV and 424 kV can be acceptable for less than 20 minutes, or a voltage between 424 kV and 428 kV for less than 5 minutes. A too low voltage can disturb the normal operation of some protections and transformer on-load tap changers, electronic power based load or affect the behavior of the auxiliaries of generation units.

Contractual ranges for customers

For customers and distributors, each supply contract defines the declared supply voltage value and the accepted variation range around this value or thresholds. These two terms, depending on the sizing of customers equipment connected to the network, must be respected at all times.

Voltage collapse and critical voltage

For each operational situation there is a maximum active power that can be transmitted through the network. This point is called the critical point and represents the point where the system collapses. As long as the load increases, the power transmitted to supply the load also increases meanwhile the voltage profile of the network decreases in inductive network. Close to the critical point, a small increase of the demand/load implies a great decrease in the voltage level of the network (see illustration 2.1.a).

The critical value of the voltage of each node of the grid is a function of the characteristics of the grid and of the load (inductive or capacitive) and of the location of the reactive compensation means. The margins to keep voltage secure depend on reserves of reactive power available at generating units or by bank capacitors. At any time, TSOs must guarantee that in N and N-1 situations (failure of one line) the voltage level is not near the critical voltage. This rule leads TSOs to determine acceptable voltage levels for the N situations and potentially different ones corresponding to N-1 situations. These voltage levels have to include margins from the critical voltage (see illustration 2.1.a).

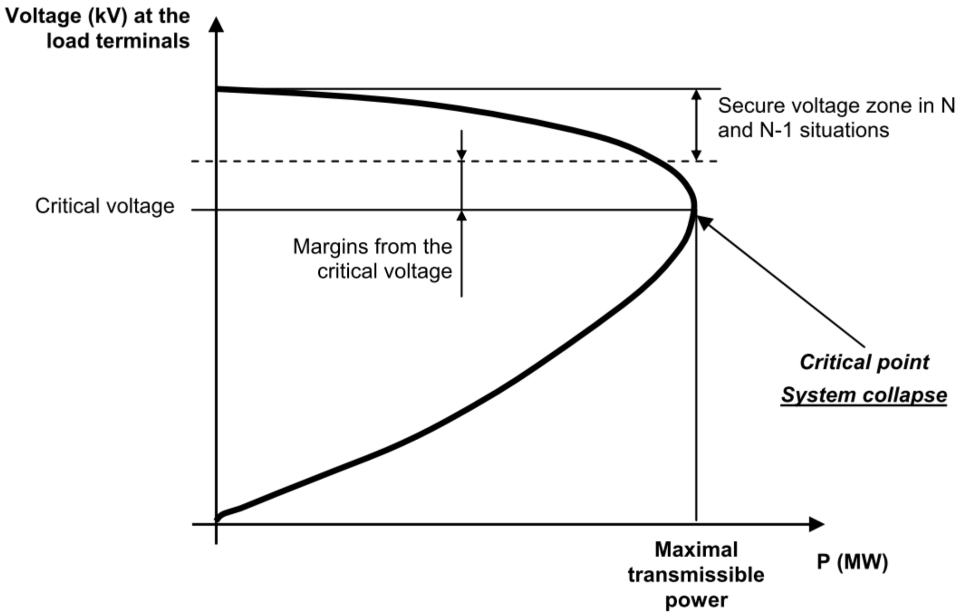


Illustration 2.1.a: Voltage behavior of a power system [OP 2009]

It becomes clear, that the UCTE Operation Handbook give no limits of the power factor or the reactive power. The TSOs are responsible to establish their own rules and regulations for third parties, generating or consuming active and reactive power, connected to the high voltage grid. These regulations are varying in depending on the TSO, the grid structure of the TSO and the current legislation. Even the transmission tariff of reactive power differs remarkably from TSO to TSO. In some countries, a tariff is applicable on the measured reactive energy or a penalty is applicable for the part exceeding predefined conditions ("ETSO Overview of transmission tariffs in Europe: Synthesis 2008", [Tariffs 2009], see illustration 2.1.b).

TransmissionCode 2007 in Germany

According to the German Energy Industry Act (Energiewirtschaftsgesetz - hereinafter „EnWG"), TSOs have an obligation to define the minimum technical requirements for connections to the transmission grids. These requirements are summarized in the so-called "TransmissionCode 2007" published in the name of all four German TSOs [TransCode 2007]. The TransmissionCode is based among others on the EnWG, the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz - hereinafter "EEG"), the EU-directive 1228/2003 and the UCTE Operation Handbook.

Concerning the reactive power exchange the TransmissionCode defines the following regulations:

<u>Reactive power consumption</u>

When active power is taken from the transmission grid, the consumer must maintain, as standard, a power factor of $\cos\varphi$ = 0.95 (inductive) to 1.00 at the grid connection point. A further exchange of reactive power is only permissible if this has been separately contractually agreed.

Country	Reactive Tariff (Y/N)	Penalty (Y/N)	Quantity/Conditions of application
Austria	No	No	
Belgium	N	Y	• Elia System Operator makes quarter-hourly deliveries of reactive power that exceed tg φ=0,329 per off take point. This leads to a term for supplementary deliveries of reactive energy, according to the article 209 §4 and §5 of the Technical Code. Voltage level (kV) – Penalty (€/MVArh): 400- 380 – 2,5 220-150 – 2,5 132-50 – 5 • In the case the offtaken active energy does not exceed, on a quarterly basis, 10% of the valid subscriptions at any given point, the additional delivery of reactive energy will be defined as the excess in respect of 32,9% of the 10% of the valid subscriptions at that point. • In the case in offtake regime, the *capacitive* reactive power doesn't exceed the following limit values, penalty for supplementary deliveries of reactive energy equals 0€/MVArh. Voltage level (kV) – Limit values capacitive reactive power (MVAr): 400- 380 – 9 220-150 – 9 132-50 – 2,5
Bulgaria		Yes	Penalty is imposed to users with connection capacity ≥ 100 kW The calculation of the quantity of reactive power for which the penalty is imposed is according to formula: $Erp = Erconsumed - 0.49\ Eaconsumed$ Where, Erp – Q-ty of reactive power for which penalty is imposed $Erconsumed$ - Q-ty of consumed reactive power by the user 0.49 – coefficient, corresponding to $\cos\varphi = 0.9$ $Eaconsumed$ - Q-ty of consumed active power by the user The penalty for consumed reactive energy is 10% from the market wholesale price of the active energy The penalty for injected reactive energy is 100% of the market wholesale price of the active energy
Czech Republic	No for EHV	No for EHV	There is penalty charged to subjects connected to DSO. Penalty is charged by DSO. The volume is 14.8 Eur/MVArh (1 Euro =27 Czech Crown)
Denmark	N	N	n/a
Estonia	Y	N	1,1 EUR/MVArh for each MVArh at 110kV only
Finland	N	Y	
France	N	Y	If reactive energy/active energy >0.4 for each connection point from 01/11 to 31/03 (on working days and 6h-22h): *1.3 c€/kvarh is invoiced for 400-380 kV customers *1.39 c€/kvarh is invoiced for 220-150 kV customers * 1.55 c€/kvarh is invoiced for 132-50 kV customers
Germany	N	N	
Greece	N	N	
Hungary	N	N	
Ireland	N	N	
Italy	N	Y	For the new regulatory period (2008-2011) a charge in c€/Kvarh is applied to the distributors/Terna for reactive energy withdrawn from the transmission grid/distribution grid exceeding a certain threshold of active energy. The charges are listed in the table below – Italy Table 1. The difference paid/received by Terna increase/decrease the amount of the ancillary services. There is also a charge issued by the distributors and paid by the final consumer for reactive energy withdrawn from the distribution grid exceeding a certain threshold of active energy.
Lithuania	Y	N	Tariff is paid by consumers above ≥30kV except households. Tariff is 5.79 €/MVarh for consumed 1 MVarh and 11.58 €/MVarh for generated 1 MVarh.
Netherlands	N	N	Regulation doesn't apply to agreements between the TSO and customers/DSO about reactive energy. This subject is included in the connection contract.
Norway	Y		Approximately 400 Mvar. Tariff is applied in point of connections where Mvar has a negative cause for the system.
Poland	N	N	There are not any rates nor penalty fees for reactive energy in TSO's transmission tariff in Poland. Only DSOs in their tariffs apply additional fees (penalties) for energy taken off from medium and high voltage network, in cases where phase factor tgφ is above 0,4.
Portugal	N	Y	The reactive energy consumed outside the off-peak hours, which exceeds 40% of the active energy consumed in the same period, must be invoiced.
Romania	Y	N	The difference of the quantity between cosφ=0.92 and cosφ=0.65
Slovak Republic	N	N	
Slovenia	Y	Y	Cos fi = 0,95
Spain	N	Y	A charge in €/MVArh is applied to the reactive energy consumption exceeding the 33% of active energy consumption. The charges are the following: 0,01 €/MVArh, if 0,90 < cosΦ < 0,95 13,091 €/MVArh, if 0,85<cosΦ<0,90 26,182 €/MVArh, if 0,80<cosΦ<0,85 39,274 €/MVArh if cosΦ<0,80
Sweden	N	N	Limits set per point of connection

Italy (Table 1)

Reactive Energy between 50% and 75% of active energy	Reactive Energy over 75% of active energy
c€/Kvarh	c€/Kvarh
0,86	1,1

Illustration 2.1.b: Transmission tariffs or penalty of reactive power [Tariffs 2009]

Reactive power exchange for generating units

At active power output each generation unit connected to the transmission grid have to fulfill the minimum requirements for reactive power delivery shown in the illustrations 2.1.c, 2.1.d and 2.1.e. The selection of the variant 1, 2 or 3 is made by the TSO in dependence on the grid needs.

In general, it must be possible to pass, within a few minutes, through the agreed configuration range for the power factor at any active power output. The entire process must be possible as often as required. If necessary, equipment must be provided as an additional requirement in the generating plant so that voltage and reactive power regulation can be carried out for all operating points within the basic requirements.

The basic requirements are also valid for generating units using renewable energy sources

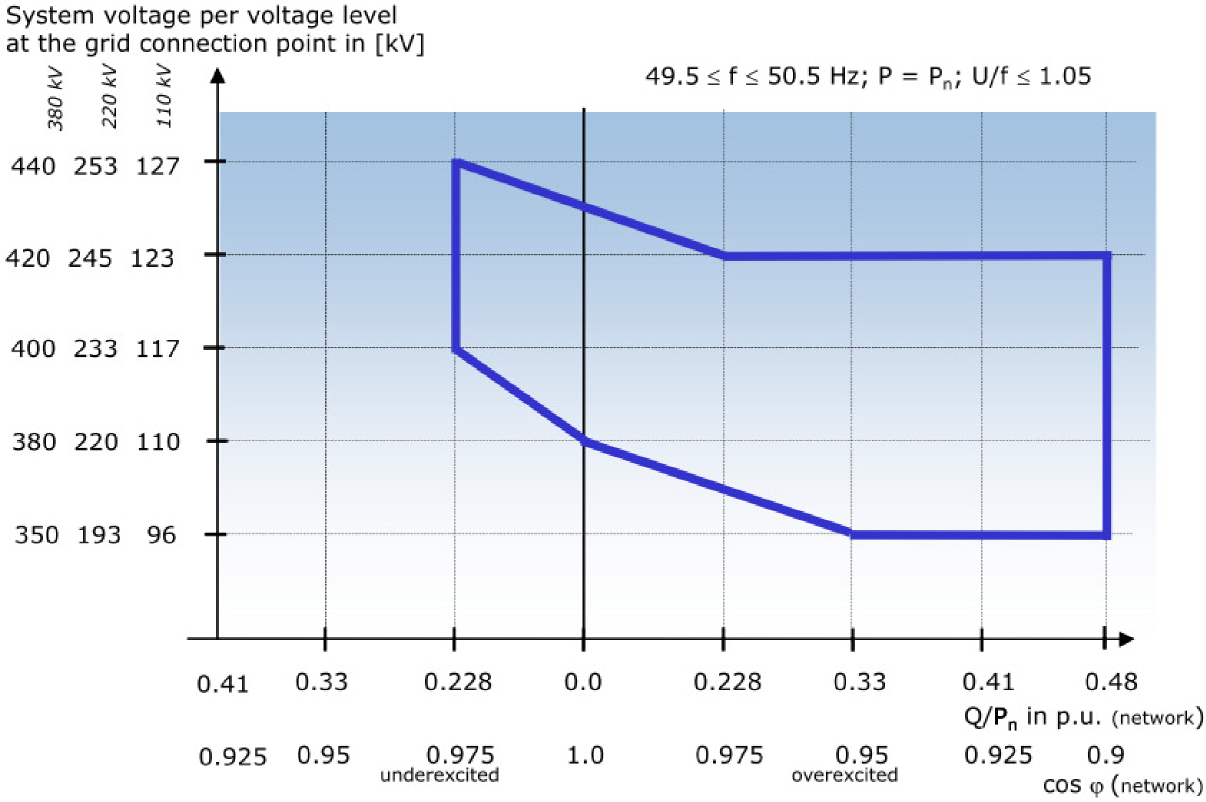


Illustration 2.1.c: Variant 1 of the basic requirement upon the network-side supply of reactive power from generating units to the high voltage network in Germany [TransCode 2007]

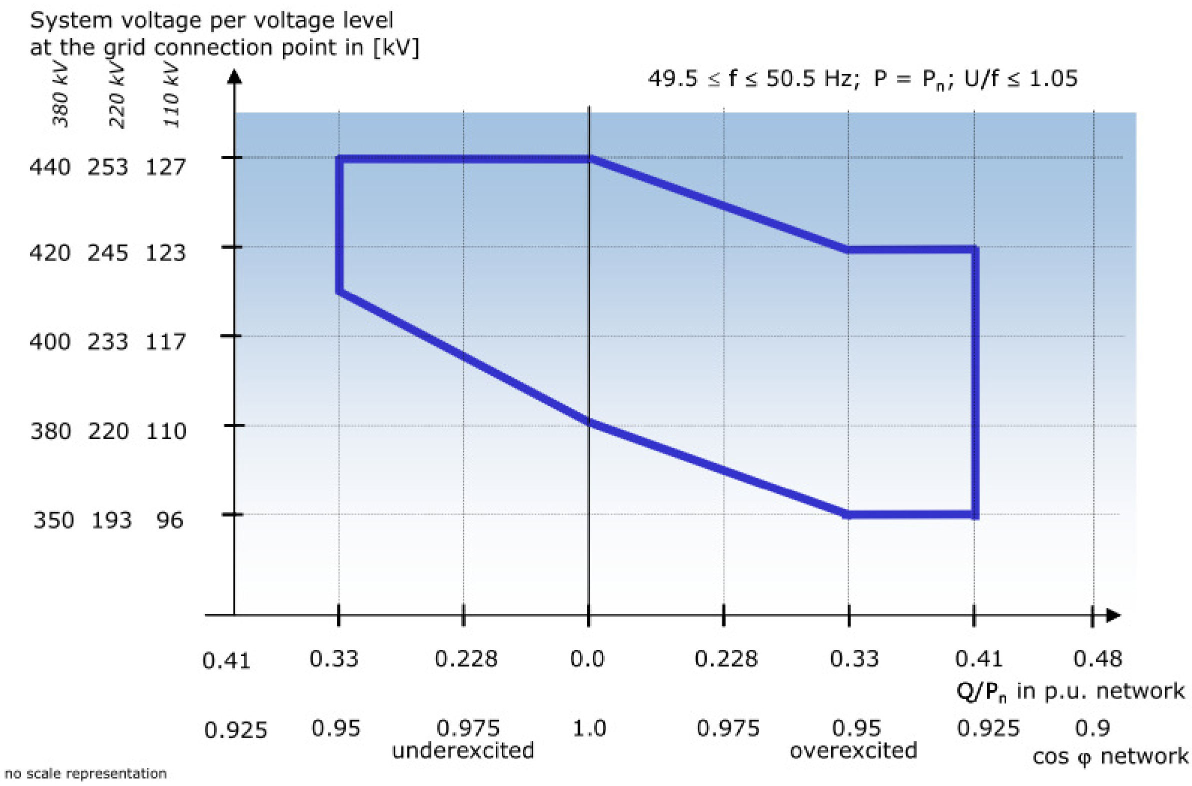


Illustration 2.1.d: Variant 2 of the basic requirement upon the network-side supply of reactive power from generating units to the high voltage network in Germany [TransCode 2007]

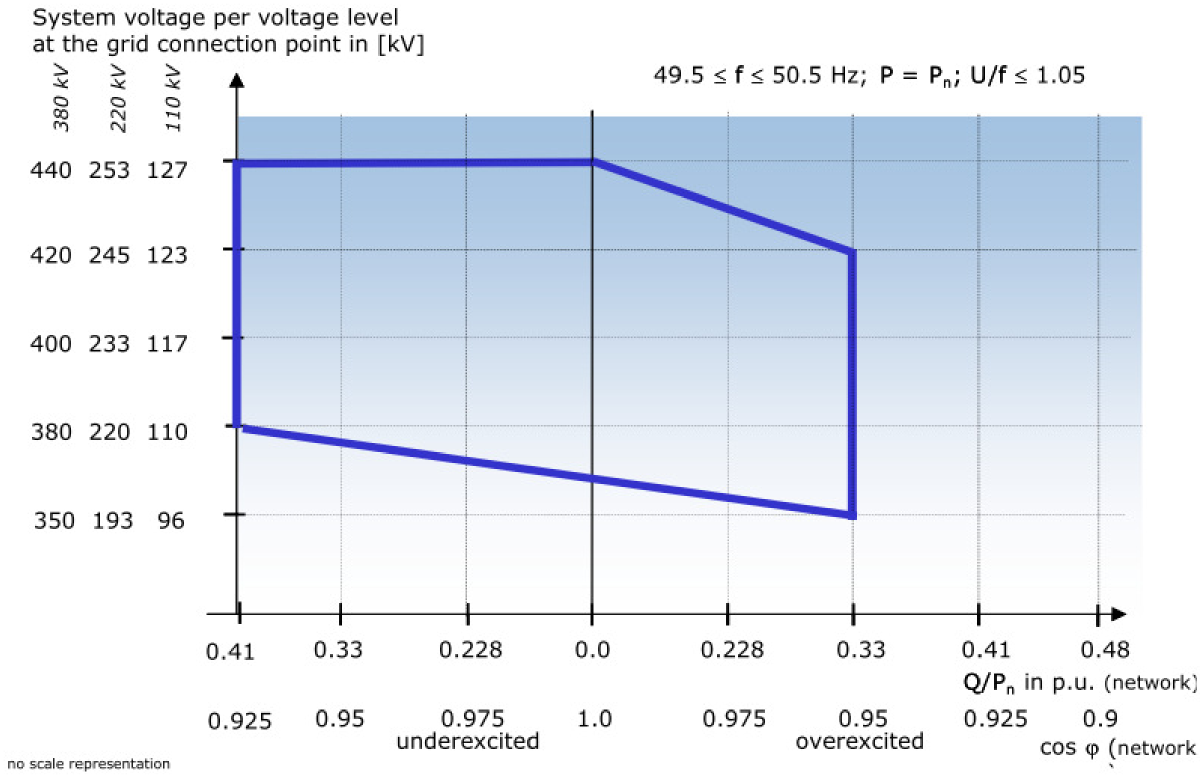


Illustration 2.1.e: Variant 3 of the basic requirement upon the network-side supply of reactive power from generating units to the high voltage network in Germany [TransCode 2007]

2.2 Regulation of power factor in medium voltage grids

Consumer of reactive power

For loads connected to the medium voltage grid in Germany the “Technical Connection Requirements for the Connection to the Medium Voltage Grid” (“Technische Anschlussbedingungen für den Anschluss an das Mittelspannungsnetz - TAB Mittelspannung 2008 [TABMedium 2008]) is valid. It defines that the power factor *cos φ* must be between 0.9 (inductive) and 0.9 (capacitive), if no other closer values are specified by the network operator.

Additionally the reactive power compensation must depend on the power factor *cos φ* or in the case of individual compensation must be switched on and off together with the related consumer load. Load-independent static reactive power compensation is not permissible. The use of filter impedances to avoid overload of the compensation means in the case of harmonics has to be agreed with the network operator.

Medium Voltage Guideline for generating units

For generating units connected to the medium voltage grid in Germany the “Technical Guideline - Generating Plants Connected to the Medium Voltage Network” (me-

dium voltage guideline - “Mittelspannungsrichtlinie”) from June 2008 is mandatory [TGMedium 2008].

The medium voltage guideline summarizes the essential aspects which have to be taken into consideration for the connection of generating plants to the network operator’s medium voltage network. The guideline considers the security and reliability of network operation in accordance with the provisions of the EnWG in the light of a growing share of dispersed generating plants (using e.g. renewable energies). The requirements of the EEG have been adequately taken into consideration and the aspects of voltage quality determined in EN 50160 (see chapter 5.4) are included.

Concerning reactive power of generating units connected to the medium voltage grid the medium voltage guideline has specified in chapter 2.5.4 the following requirements [TGMedium 2008]:

With active power output, it must be possible to operate the generating plant in any operating point with at least a reactive power output corresponding to a power factor at the network connection point of $\cos \varphi = 0.95$ (underexcited) to 0.95 (overexcited). In the consumer reference arrow system, that means operation in quadrant II (underexcited) or III (overexcited). Values deviating from the above must be agreed upon by contract.

With active power output, either a fixed target value for reactive power provision or a target value variably adjustable by remote control (or other control technologies) will be specified by the network operator. The setting value is either

a) a fixed power factor cos φ or
b) a power factor cos φ (P) (see illustration 2.2a for an example) or
c) a fixed reactive power in MVar or
d) a reactive power/voltage characteristic Q(U).

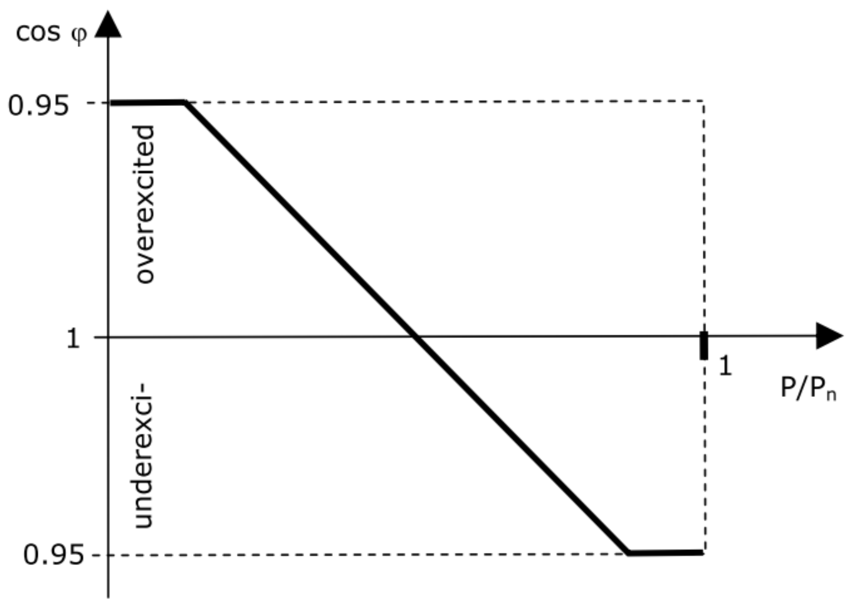


Illustration 2.2.a: Example of a cos φ (P) - characteristic

The reactive power of the generating plant must be adjustable. It must be possible to pass through the agreed reactive power range within a few minutes and as often as required. If a characteristic is specified by the network operator, any reactive power value resulting from the characteristic must automatically adapt as follows:

- within 10 seconds for the cos φ (P) - characteristic and
- adjustable between 10 seconds and 1 minute for the Q(U)-characteristic (specified by the network operator).

To avoid voltage jumps in the event of fluctuations in active power feed-in, it is advisable to choose a characteristic with continuous profile and limited gradient. Both the chosen approach and the target values shall be determined individually for every generating facility by the network operator. The specification can be based on

- the agreement of a value or, where applicable, of a schedule or
- online presetting of target values.

In the case of online presetting of target values, the new specifications for the working point of reactive power exchange shall be implemented at the network connection point after one minute, at the latest.

The behavior of the generating units connected to the medium voltage grid shall be verified by tests on the generating units or by means of a validated computation model of the generating plant.

2.3 Regulation of power factor in low voltage grids

Connection to the low voltage grid of both electricity consuming and electricity generation units is dealt with in the so called TAB (Technische Anschlussbedingungen). Generally, units can be connected to the low voltage grids when they fulfill the requirements of electromagnetic compatibility (DIN EN 61000-3-x). In case some predefined connection values are exceeded the operator of the connected unit has to get the permission of the distribution grid operator.

With respect to the power factor no overall criteria are given. But TAB gives for some specific applications limits for the power factor.

Discharging lamps

Customers in distribution grids are allowed to connect discharging lamps up to a nominal power of 250 W per phase without any compensation measures. For larger discharging lamp capacities the power factor has to be held within the limits of 0,9 (capacitive) and 0,9 (inductive).

In case the installed capacity is exceeding 5 kVA one of the following measures has to be applied:

- Switching in different groups where half of the power is connected with capacitive ballasts and the other half with inductive ballasts
- Application of electronic ballasts that guarantee a power factor of 1.
- Compensation via a centrally installed inductive power compensation unit at the customer site that does not influence audio frequency ripple control

Motors

For motors limits are given in terms of power and starting currents. There are no power factor requirements given for motors.

Welding equipment

For welding equipment with an installed power exceeding 2 kVA customer and grid operator agree upon measures that do not influence the grid and other customers. The units should charge the different phases almost equally. The power factor should be at least 0,7 inductive.

Reactive power compensation installations

Additionally the reactive power compensation must depend on the power factor or in the case of individual compensation must be switched on and off together with the related consumer load.

The use of filter impedances to avoid overload of the compensation means in the case of harmonics has to be agreed with the network operator.

Connection of electricity generation units

Concerning electricity generation units there are no specifications concerning the power factor so far. Penetration of the low voltage grid with generation units is still low and those units generally feed their electricity to the grid with a power factor of one. In future with higher shares of photovoltaics and micro CHP that might change.

2.4 Costs for reactive power provision

A data analysis of [ENE'T 2007] of more than 800 network operators shows that German distribution network operators charge on average 1.1 c€/kvarh (within the range of 0.0-2.7 c€/kvarh) if the power factor is lower than 0.9_{ind} (in average). In the high voltage network the average charge is 1 c€/kvarh (0.0–1.5 c€/kvarh) and in the extreme high voltage one network operator has a charge of 0.3 c€/kvarh.

3 Measurement of reactive power and power factor

In general the reactive power and the power factor are determined from the time-depending voltage and current measurements. The precise measurement of active and reactive power and power factor is important especially for metering, while the grid management itself is based on controlling voltage and frequency (see chapter 4). Metering means acquiring the amounts of power supplied from the power provider or distributor to the consumer. The main characteristic of the needed meters, which are similar in high, medium and low voltage grids, are summarized in chapter 3.1. To measure voltage and current in high voltage transmission and medium voltage distribution grids appropriate instrument transformers or sensors are used, which are described in chapter 3.2.

3.1 Characteristics of power meters

Meters for billing electrical power consumption have special characteristics, especially a high accuracy. In Germany, for instance, they have to meet the requirements of the PTB ("Physikalisch-Technische Bundesanstalt") to be certified and approved. Similar requirements exist in other countries.

In principal there exist two different types of power meters, the electromechanical and the electronic type. In Illustration 3.1.a some further main characteristics are summarized.

Criterion	Alternatives
Connection	direct or to instrument transformer
Type	electromechanical or electronic
Mounting	surface-mounted housing, live parts fixed
	flush-mounted housing, live parts fixed
	flush-mounted housing, live parts removable
	subrack, live parts on circuit boards
Current	alternating current
	three-phase in 3- and 4-wire systems loaded symmetrically and asymmetrically
Power	active and reactive consumption, incoming and outgoing
Tariff	single or two-rate tariff

Illustration 3.1.a: Selection criteria and alternatives for power meters [Gremmel 2006]

Electromechanical meters are still used especially in the low voltage grid. They work like an induction motor whose speed is directly proportional to the applied voltage and the current flowing through it. The phase displacement of the current is automatically taken into account by the meter, so that the speed of the moving element (aluminum disc) is proportional to the active power or in some cases to the reactive power (depending on the wiring of the used coils). The number of revolutions of the disc

is proportional to the energy consumption. Further information can be found for instance at http://www.usbr.gov/power/data/fist/fist3_10/vol3-10.pdf.

Electronic meters are state-of-the-art and they use the principle of digital multiplication and integration. The measured values of current and voltage are digitized using high-precision A/D converters with a high sampling frequency of e.g. 2400 Hz. The digitized values are forwarded to a DSP (digital signal processor), which calculates the active, reactive and apparent power, the power factor and the needed energies. The advantages of this electronic analysis are the high integration of measurement functions, low fault rate and the option of a full 4-quadrant measurement [Gremmel 2006].

3.2 Measurement in high voltage and medium voltage grids

In high voltage transmission and medium voltage distribution grids the time-depending voltage and current are measured by appropriate instrument transformers or sensors both for voltage and current, which are installed at the busbar and / or in the feeders of a substation. The kind, number and position of instrument transformers depend on the operational requirements as well as on the protection scheme. For example voltage transformers in the feeders are used for measurement and protection. Voltage transformers at the busbar are convenient for measurement purpose, so that there is no need to calculate missing values [Gremmel 2006].

Electrical instrument transformers transform high currents and voltages to standardized low and easily measurable values that are isolated from the high or medium voltage. When used for metering purposes, instrument transformers have to provide voltage or current signals that are very accurate both in magnitude and phase. When used for protection purposes, the instrument transformer outputs must accurately represent the transmission line values during both steady-state and transient conditions. These critical signals provide the basis for circuit-breaker operation under fault conditions, which are fundamental to network reliability and security. Instrument transformers used for network control supply important information for determining the state of the operating conditions of the network [Siemens 2008].

3.2.1. Current transformers

A current transformer has a primary winding, which is incorporated in the line and carries the current flowing in the network. For current measurement it is possible to provide different secondary windings, each for a different function (metering, protection, network control).

In medium voltage applications current transformers are usually designed as post-type or bushing transformer insulated by cast resin. Voltage transformers for high voltage application are in general designed with oil-paper or SF_6 insulation. There

exist in principle three different types of voltage transformers, which are shown in illustration 3.2.1.a: [Gremmel 2008]

- **Top-core current transformers** have a short primary conductor with low thermal losses, a high current and short-circuit current capacity and a slim insulator. The location of the secondary cores at the top leads to a high centre of gravity and increased stress on the insulator. Therefore top-core current transformers can not be used in areas with high earthquake risk.
- **Tank-type current transformers** have a long primary conductor leading to high thermal losses and limitations of current and short-circuit current capacity. But the location of the secondary windings in the base tank leads to a low centre of gravity.
- **Eye-bolt current transformers** are hybrids between the other types for special applications providing a compromise between the main characteristics.

Besides the current measurement at power frequency (50 current transformers are usually able to analyze the whole area of harmonic currents with sufficient accuracy [Hormann 2005].

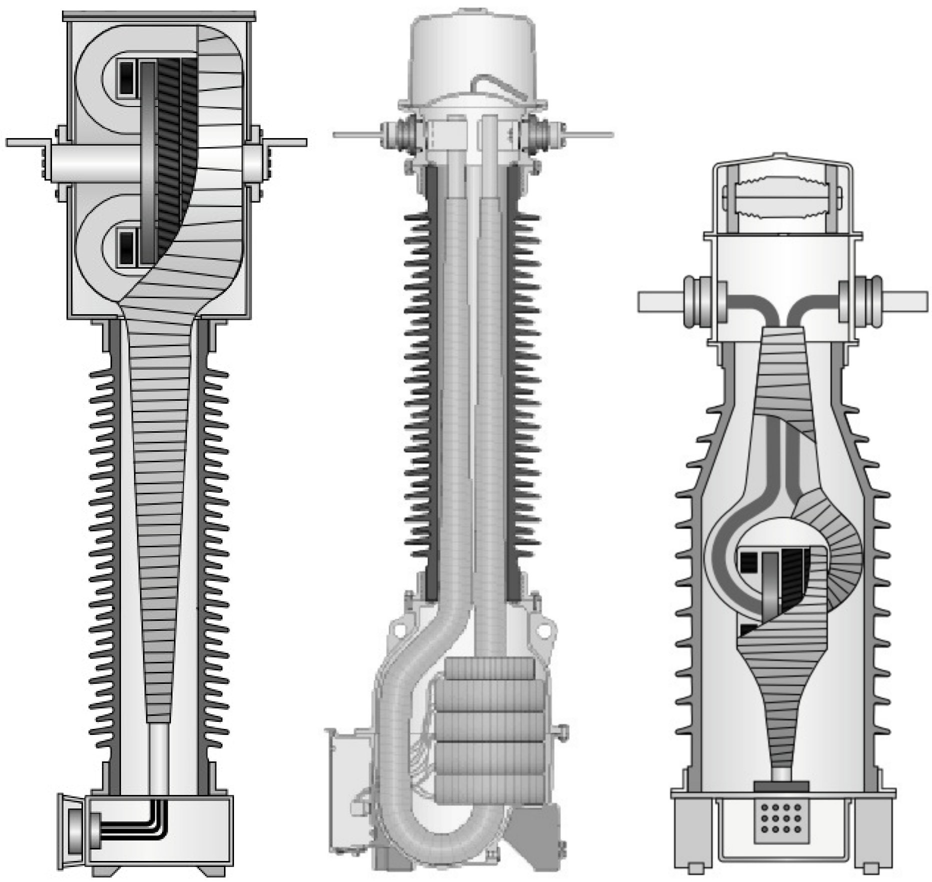


Illustration 3.2.1.a: High-voltage current transformers: top-core current transformers, tank-type current transformers and eye-bolt current transformer (from left) [Gremmel 2006]

3.2.2. Voltage transformers

Voltage transformers can be divided into inductive and capacitive voltage transformers. Inductive voltage transformers are the most economical solution for voltages up to 145 kV. Up to a voltage of 765 kV capacitive voltage transformers are used, which consists of a capacitive divider and an inductive (medium voltage) transformer. Again transformers for the high voltage application are in general insulated by oil-paper or SF_6, while medium voltage transformers are cased by epoxy resin [Gremmel 2008].

Voltage transformers in medium and high voltage grids can be used for voltage measurement up to 500 Hz, in some cases up to 1 kHz. This means that also harmonics can be analyzed up to order 10 and 20, respectively [Hormann 2005].

3.2.3. Voltage and current sensors

Different sensors to measure voltage and current in medium and high voltage applications are available. Currents can be measured by Rogowski-coils or optical transformers using the Faraday Effect, voltages are determined by ohmic or capacitive dividers. The voltage signal sent by a sensor is some orders of magnitude smaller than the signal of a conventional instrument transformer. Therefore sensors are in general only suitable for digital secondary devices, like electronic meters. But sensors have the following advantages:

- High linearity
- Large dynamic range
- Small dimensions and light weight
- Simplified engineering and lower costs

Despite these advantages sensors are not used in all new installations, as some customers (network operators) trust more in the conventional technique.

4 New challenges and opportunities related to increasing renewable energy based grid-connected decentralized power generation

In chapter 1.1 the need for reactive power, the role of $\cos\varphi$ and the means how reactive power is provided in nowadays interconnected electricity systems has been analyzed. That means that a major fraction of the grid infrastructure's need for reactive power is provided by large synchronous generators that are driven by the turbines of large and centralized power stations.

The centralized electricity generation in large power stations therefore on the one hand guarantees the transmission of (active) power with low losses and on the other hand the voltage levels in the transmission grids are kept within agreed limits which ensure stability of the complete electricity supply system.

In this chapter the consequences on reactive power supply and system stability will be discussed when more and more renewable and fluctuating electricity generations systems and small and decentralized power stations of the type combined heat and power and combined heat cold and power stations will replace the large centralized power stations. Is it still possible to have reliable and stable electricity supply systems?

The next subsection will start with a review on voltage / reactive power control and which strategies can be maintained and which new strategies can be applied in future. In further subsections the frequency control aspect will be discussed before other relevant system services that affect system stability are dealt with.

4.1 Voltage – reactive power Control

Maintaining voltages within tolerances is an obligation of grid operators. If voltages get outside of agreed limits (e.g. EN-50160) grid operators have to interact or if not possible they have to interrupt supplies to customers.

Three different levels of voltage control can be distinguished and are explained in the following:

- Primary power/voltage control,
- Secondary power/voltage control, and
- Tertiary power/voltage control.

The explanations focus on reactive-power/voltage control. It has to be mentioned that also active power control can influence the voltage and may be controlled in addition to provide optimal control results.

Primary Voltage Control

Similar to primary frequency control, primary voltage control is an automatic local control of the reactive power source itself. Generally, droop functions as given in illustration 4.1.a are applied to stabilize the voltage at the unit’s terminal by feeding-in capacitive currents up to $+\Delta Q$ if the voltage reaches its minimum acceptable limit of $U_n - \Delta U$. In contrast, if the voltage reaches its maximum acceptable limit of $U_n + \Delta U$ inductive currents of $-\Delta Q$ are injected. These reactive power control actions have indirectly an influence on the voltage within seconds or even faster.

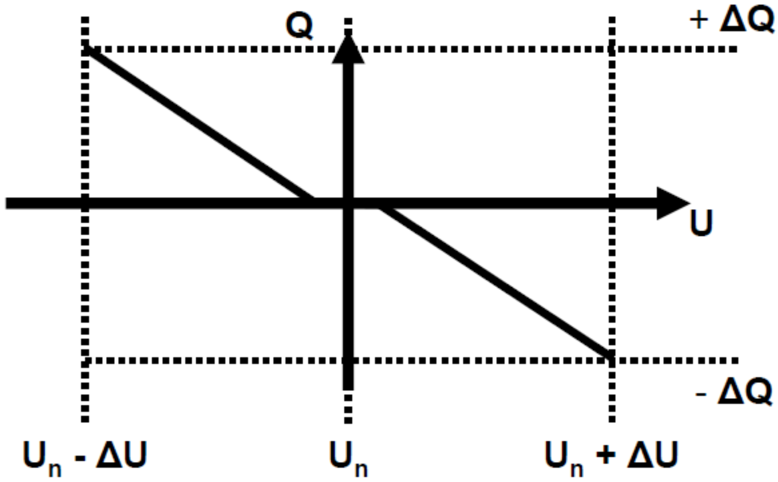


Illustration 4.1.a: Reactive power / voltage droop [Braun 2008]

Secondary Voltage Control

Secondary Voltage Control consists on the measurements of the voltage magnitude in some critical buses of the system. These buses are known by the operator as the result of its experience in the control of the system. So, if the voltages at these buses are out of range, the operator is going to change the setting points of the voltage regulators (generators) in order to recover a voltage profile in the normalized interval. The time response of the voltage secondary control goes up to one minute and less than several minutes [CRISP 2004]. Secondary power / voltage control is controlled centrally but automatically in the control centre of the network operator.

Tertiary Voltage Control

Tertiary Voltage Control is used by the grid operator. The grid operator optimizes the system voltage profile and provides reference values of the secondary voltage control. Normally the tertiary control operates in a 15 minutes cycle [CRISP 2004]. The tertiary power / voltage control is applied in the control centre of the grid operator

Consequences in a changed electricity supply structure

Grid-forming generators provide voltage control by defining the terminal voltage value. This voltage is reduced due to the voltage fall over the grid impedances until the power flow reaches the loads. In between, voltage levels can be changed via transformers. These transformers can change their winding ratio by tap changers to set a new starting voltage value for the lower voltage grid.

If the grid voltage is established by grid-forming units, the indirect control of voltage by apparent power injection and extraction can be applied. This indirect control is called power/voltage control and can be separated in three control levels as described before.

In a high voltage grid whose reactance exceeds its resistance, reactive power transfer depends mainly on voltage magnitudes. It is transmitted from the side with higher voltage magnitude to the side with lower voltage magnitude. Reactive power cannot be transmitted over long distances since it would require a large voltage gradient to do so. Therefore, voltage control has to be locally distributed.

That means when the centrally arranged large power stations are replaced by more distributed (and smaller) power stations even could improve the situation of reactive power provision – in case renewable energy systems are capable of providing the service – as they will be placed at more grid nodes. Independent from the future arrangement of power generators the opportunity of placing compensation facilities will remain. In contrary, when distributed generation is placed in many grid nodes it could make compensation facilities unnecessary or further reactive power compensators like FACTS might be avoidable.

Distributed generators also feed into the low voltage grid. But that does not mean that voltage control in low voltage grids can be applied like in medium and high voltage grids. The difference is that low voltage grids have more resistive behavior $(R >> L)$. That means that here voltage control is mainly influenced by active power distribution. For future grids here so-called “smart grid” technologies can be applied as “Demand Side Management”, “Demand Response” and “Vehicle to grid” strategies.

4.1.1 Voltage control ability of wind turbines

Wind turbine generators consist of a chain of power conversion processes. Kinetic energy of the wind is converted by the rotor into mechanical energy. (Sometimes) mechanical energy is transferred to the electrical generator via a gear to adopt the mechanical speed better to the generator characteristic. Either directly or after a frequency conversion process the generator feeds the grid via a transformer (Illustration 4.1.1.a).

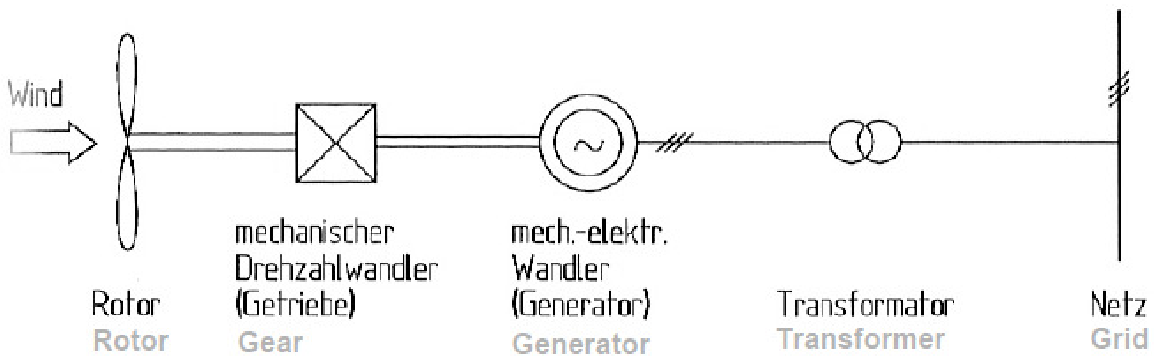


Illustration 4.1.1.a: Conversion chain of a wind turbine generator

Reactive power control capability mainly depends on the grid-coupling converter. Wind turbine generators can mainly have four types of grid-coupling converters:

- directly-coupled induction generators in fixed speed or variable slip design with capacitor banks
- doubly-fed induction generators with a power electronics converter between the point of grid connection and the rotor circuit of the induction generator
- Inverter-coupled generators with a full power electronics converter that couples different designs of induction and synchronous generators.
- directly-coupled synchronous generators with a dynamic gearbox and with excitation system

Directly coupled induction generators

The rotor of an induction generator has no active control capability of the magnetic field. When connected to the grid the stator windings create a magnetic field in the air gap. Rotating the rotor windings of the induction generator in the magnetic field of the stator induces currents in the rotor that also produce a magnetic field. If the rotor field turns faster than the stator field the induction generator acts as a generator injecting active power into the grid. The creation of the magnetic field requires reactive power.

Therefore, a wind turbine generator with directly coupled induction generator (illustration 4.1.1.b and illustration 4.1.1.c) itself is not capable of controlling reactive power independently from the active power. It even needs capacitive reactive power to magnetize its inductances.

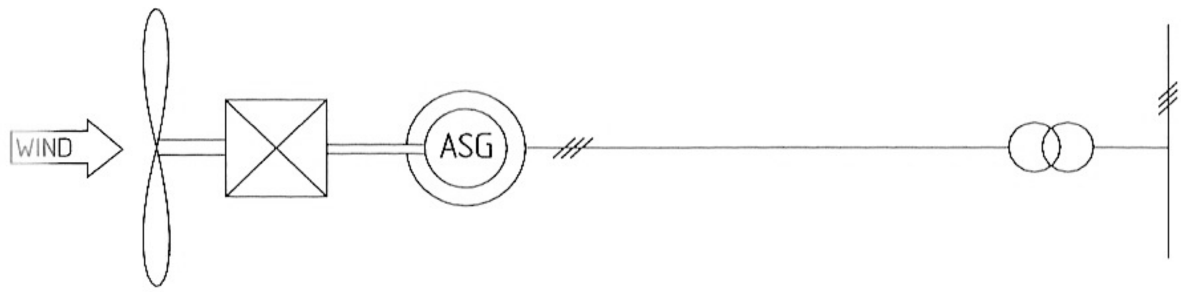


Illustration 4.1.1.b: Wind turbine generator with directly coupled induction generator

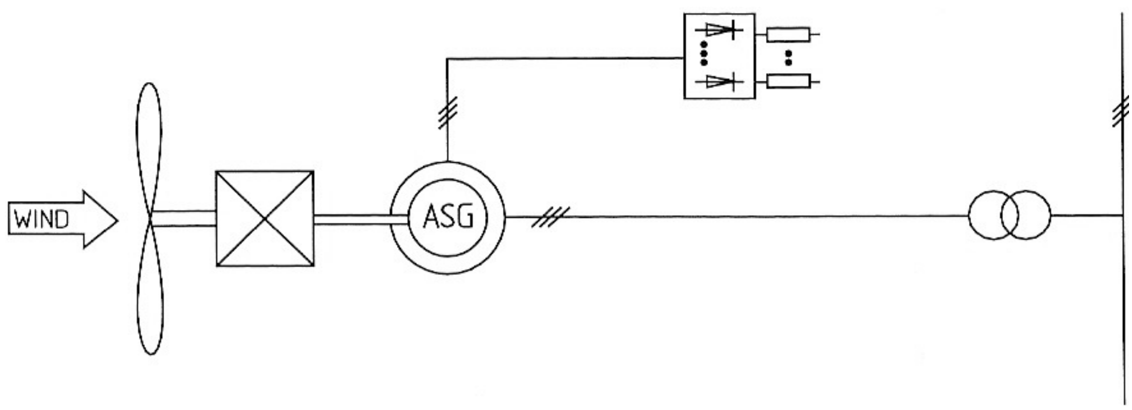


Illustration 4.1.1.c: Wind turbine generator with directly coupled induction generator and variable slip design

This type of wind turbine generator even cannot be connected to the grid in large quantities without further methods for reactive power compensation. Directly coupled induction generators have been the mostly applied concept in the 1990ies. Nowadays they do not play a major role anymore – at least not in large wind turbine generators.

Wind turbine generators with directly coupled induction generators can be equipped with external reactive power compensation devices. With this the reactive power demand from the grid can be reduced. Reactive power control is possible with this additional equipment. However, the control results from the separate equipment and not from the induction generator itself.

Double fed induction generators

The DFIG comprises an IG and two power electronic converters (illustration 4.1.1.d). DFIGs have a rotor excitation like SGs and the IG can be magnetized with reactive power that is supplied by the rotor side inverter.

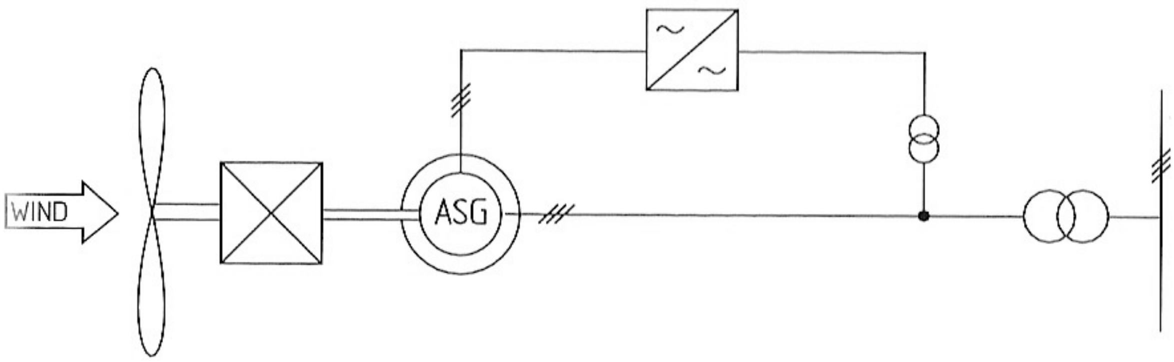


Illustration 4.1.1.d: Wind turbine generator with double fed induction generator

The AC/DC/AC converter is divided into two components: the rotor-side converter and the grid-side converter. Generally, both are of voltage source inverter type. A capacitor connected on the DC side acts as the DC voltage source. The three-phase rotor winding is connected to the rotor-side inverter, e.g. by slip rings and brushes. DFIGs are often used in wind turbines because of their capability to operate at variable speed on the rotor side. The rotor-side inverter can superpose an electrical field with a rotor frequency that adds to the mechanical rotor speed. The advantage compared to the full inverter design is that only a fraction of the full rated power of the generator system is required for the power electronic converter (typically 10 – 30%).

The DFIG design allows an excitation in the rotor coils for speed regulation and reactive power control of the IG by the rotor-side inverter as well as reactive power supply by the grid-side inverter.

Inverter coupled generators

Using power electronics increases the possibilities of power conversion significantly because the output voltage or current signal can be defined precisely with available control techniques. Not all inverter topologies allow all control functions that are described in the following but an inverter can be designed accordingly. For instance, only bipolar inverter topologies can control reactive power but not unipolar ones. Illustration 4.1.1.e shows a wind turbine generator with full inverter.

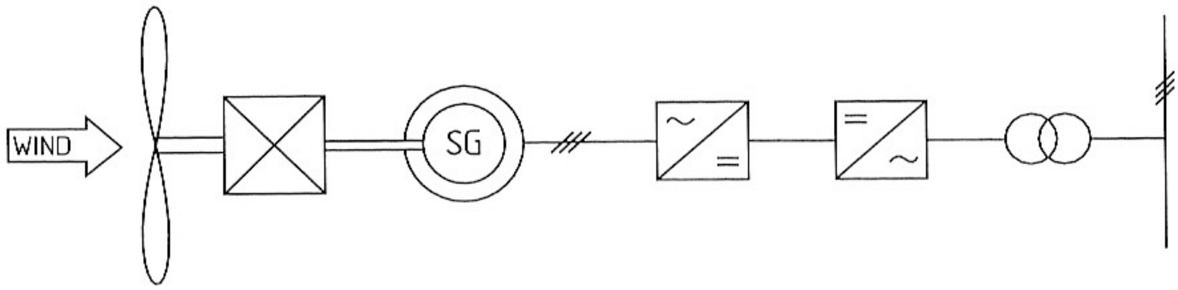


Illustration 4.1.1.e: Wind turbine generator with full inverter

Inverters can be distinguished in line-commutating inverters and self-commutating inverters. Line-commutating inverters need the grid's voltage for operation but self commutating inverters are able to operate without. Thus, self-commutating inverters in contrast to line-commutating inverters are capable of defining frequency and voltage themselves. Actual inverters in distributed generators are self-commutating using IGBTs as switching devices.

Depending on their DC-Link characteristics, inverters can also be classified as Current Source Inverters (CSI), Voltage Source Inverters (VSI) and Z-Source Inverters (ZSI). An overview of these classification and their characteristics provide [Bülo et al 2007]. The most common type of inverter is the VSI that has a voltage source characteristic, normally backed up with capacitors in parallel to the DC-Link.

When the inverter is operated in grid-forming mode (Vf-controlled), the inverter detects only the load impedance and thus only the voltage resulting from the voltage divider between the load and the coupling impedance. The inverter will then try to retrieve the nominal voltage set point by increasing the amplitude of its internal voltage and by changing its virtual impedance. With adequate switching also the frequency can be defined.

When the inverter is operated in grid connected mode (PQ-controlled), the inverter can adjust its internal voltage to be able to provide the set points of active and reactive power. In grid connected operation a current is injected. If it is in phase with the grid's voltage only active power is provided. Switching adequately, a phase shift between the terminal voltage curve and injected current curve causes reactive power supply.

One fundamental limit is the maximum current transfer of the inverter. As long as the absolute value of the current does not exceed the limit the phase angle of the current vector can be arbitrarily controlled. It is possible to control active and reactive currents independently from each other with response times in the order of milliseconds.

Originally, the main purpose of wind turbine generators is to feed active power to the grid. Therefore the components of the conversion chain of a wind turbine generator are designed. Whether a wind turbine generator can deliver reactive power or not depends on – among other criteria – the actual active power generation.

Intermittent renewable energy converters like wind turbine generators have time variable active power generation according to the actual wind speed. The potential to deliver reactive power $Q_{\max}$ – independently of wind turbine concept – is the following:

$$Q_{\max} = \sqrt{S_{\max}^2 - P_{act}^2} \,,$$

with P_{act} the actual active power delivery and $S_{\max}$ the rated apparent power.

If the grid coupling converter is sized to match exactly the rated active power generation there is no capacity for reactive power left in case the wind turbine generator operates at rated wind speed.

Over sizing the converter leads to a certain guaranteed reactive power control capacity. These dependencies are shown in illustration 4.1.1.f. An over sizing of e.g. 10 % allows a secured reactive power control of ± 46 % and an over sizing of 20 % even ± 66 % of the rated power. These values increase significantly in case of a part-loaded active power generation. The lighter lines in illustration 4.1.1.b show larger reactive power supply capacities when the converter operates under part load condition with regard to active power [Braun 2008].

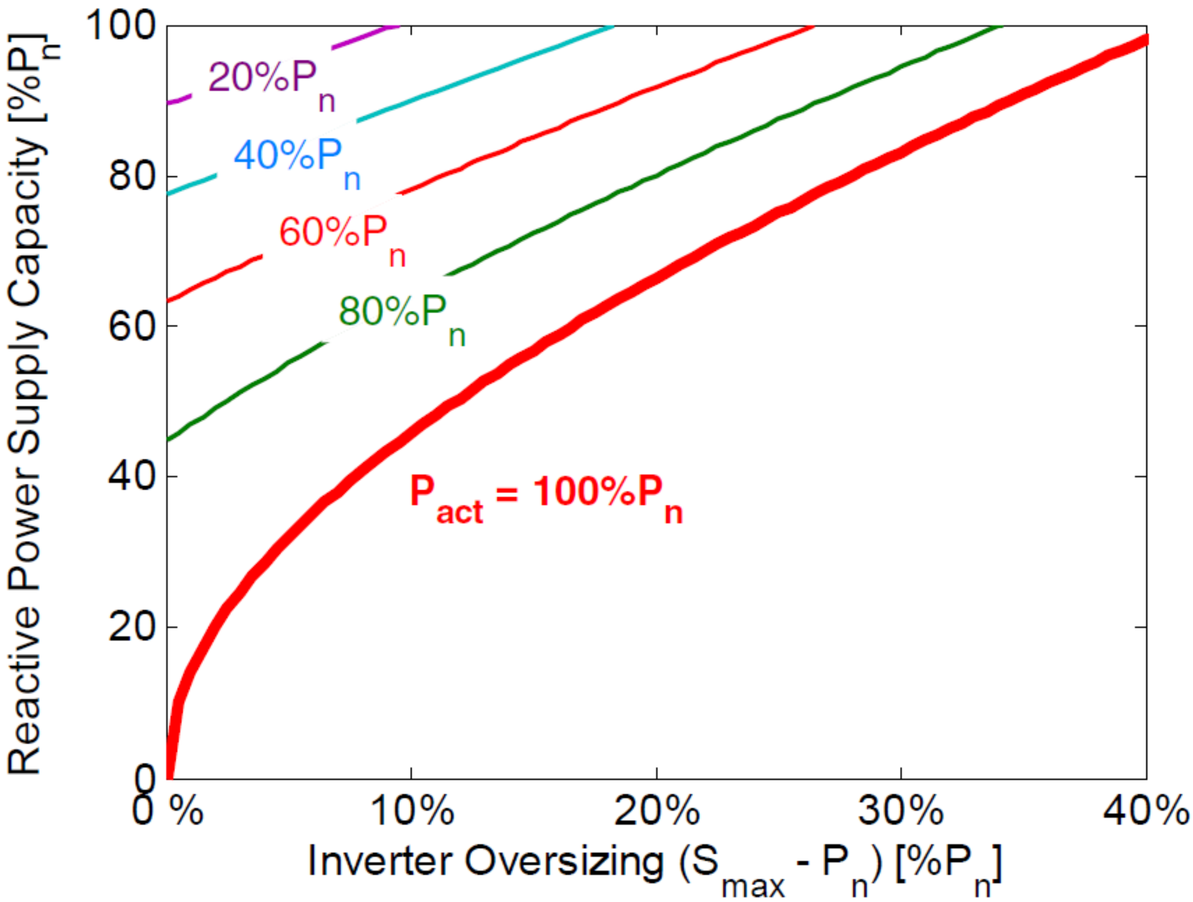


Illustration 4.1.1.f: Reactive power supply capacity as a percentage of the rated power P_n depending on the converter's over sizing $(S_{\max} - P_n)$ also as a percentage of the rated power with the actual active power P_{act} as a parameter.

Directly-coupled synchronous generators with a dynamic gearbox

New developments of wind turbine generators apply directly coupled synchronous generators. Direct coupling long time was known to be not appropriate for wind technology as the rotor speed is absolutely rigid according the relation between speed and grid frequency ($n = \frac{f}{p}$) and therefore mechanical stress with e.g. gusts lead to shorter life times. In those new wind turbine generators dynamic gear boxes are applied that allow variable speed operation of the rotor.

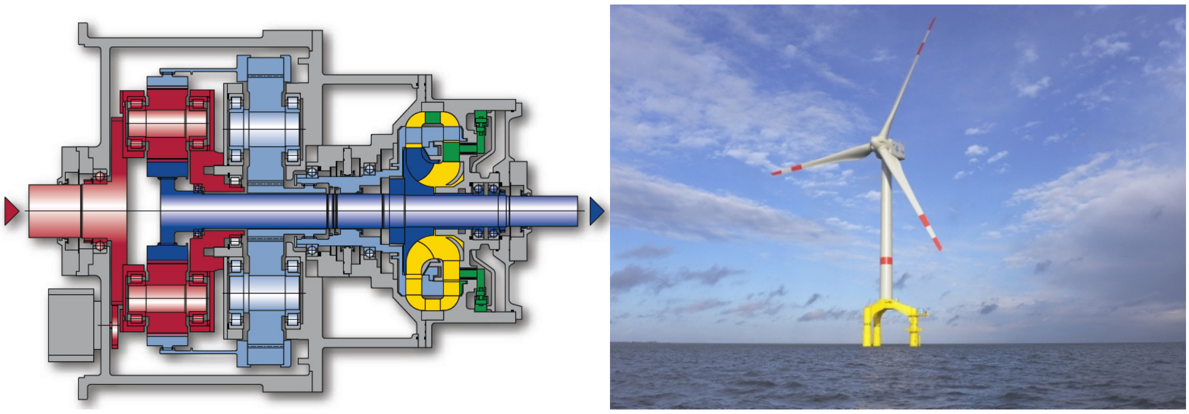


Illustration 4.1.1.f: Variable speed gear "Windrive" [Voith 2009] that is applied e.g. in wind turbine generator BARD 5.0 [BARD 2009]

Synchronous generator coupled wind turbines can provide reactive power in addition to active power by their excitation control – similar like conventional power stations do (see chapter 1.1).

Two basic types of synchronous generators exist. Either the excitation is achieved with a permanent magnet or with an excitation system. Presently, most of the permanent magnet generators are coupled with inverters to the grid. The advantage of permanent magnet synchronous generators lies in saving the excitation system with its excitation losses, its costs and its need for space. Its disadvantage lies in missing reactive power and voltage control capabilities.

Consequently, the use of synchronous generators for voltage / reactive power control is limited to synchronous generators with excitation system. Their control capabilities are described in the following. The rotor windings of a SG with excitation system are fed by DC excitation current to create a magnetic field in the air gap with a sinusoidal distribution in space. Rotating the rotor induces sinusoidal voltages in the stator windings. In grid connected operation the voltage characteristic is given by the grid. The SG has to be synchronized to the grid's voltage with regard to its voltage magnitude, frequency, phase sequence, and phase shift by use of the above described control capabilities. The rotor is then forced by the stator field to rotate with the network frequency. If the mechanical power and therewith the torque is increased on the rotor the frequency stays constant but the angular displacement between rotor axis and the magnetic field increases. In this situation, active power is injected into the grid. The angular displacement (also called internal rotor angle) is limited so that the synchronous generator cannot fall out of step. Vice versa the synchronous machine can operate as a motor if the angular displacement is negative.

4.1.2 Voltage control ability of photovoltaic systems

Photovoltaic cells and modules produce direct current. Therefore all photovoltaic systems that are connected to the grid are connected via inverters. A schematic of a grid connected photovoltaic system is given in illustration 4.1.2.a.

Therefore reactive power control is possible as all grid-connected photovoltaic systems use inverters for grid connection. The potential is assessed in the same way as described in chapter 4.1.1 – “Inverter coupled generators”.

Normally, photovoltaic inverters are operating in stand-by at night to reduce losses. In this situation the power electronic control is deactivated so that reactive power control is not possible. Therefore, reactive power supply of PV systems is limited to systems that are actually feeding power to the grid. An active system is able to control reactive power in a large range. For future requirements of reactive power control night operation generally is not a problem to be activated.

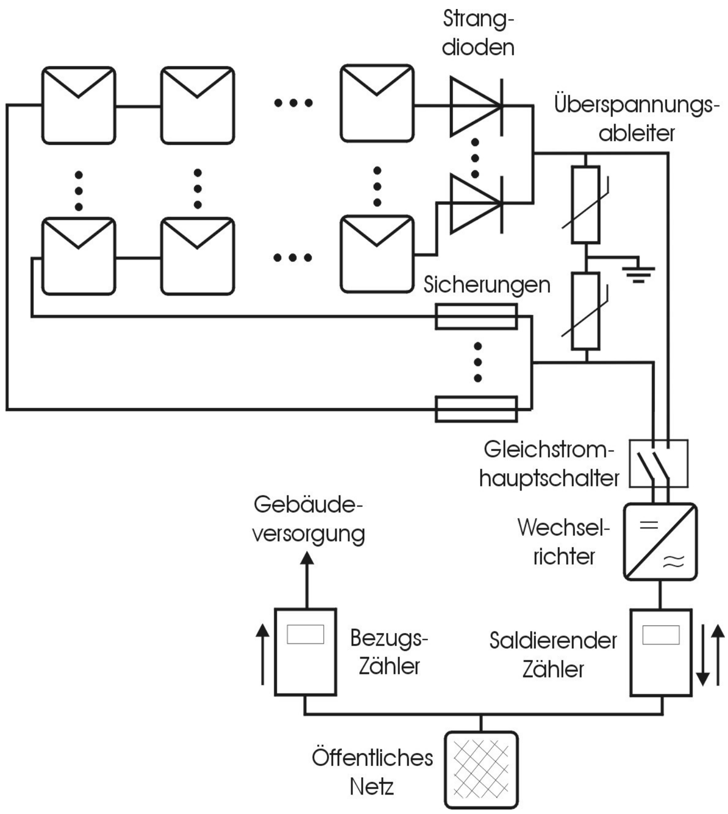


Illustration 4.1.2.a: Schematic of a grid connected photovoltaic systems (Translation: Strangdioden = string diodes; Überspannungsableiter = discharger; Sicherungen = fuses; Gleichstromhauptschalter = DC main switch; Wechselrichter = inverter; saldierender Zähler = balancing counter; Gebäudeversorgung = building power supply; Bezugszähler = counter for electricity demand; öffentliches Netz = Public grid)

The system reaches its maximum active power generation only for a short period of time during the year. Even if the inverter is not oversized the part-load operation behavior leaves sufficient reactive power control capacity.

The potential of reactive power production / absorption is high. This reactive power capacity results from the variable photovoltaic power generation that utilizes most of the time not the full capacity of the inverter. Over sizing the inverter could lead to guaranteed reactive power capacity.

4.1.3 Voltage control ability of run-of-the-river hydro power stations

Hydro power stations – and their provision of reactive power is standard all over the world and especially in Brazil. Therefore their ability is not discussed more detailed here. As they are coupled by synchronous generators they supply reactive power as described in chapter 1.2.2 – "Reactive power provision by synchronous generators".

Especially when dealing with small (or even micro-hydro or pico-hydro) hydro power stations then also other concepts than the grid connection via synchronous generators are applied. Then the capability of reactive power control provision of hydro power plants depends on the grid coupling converter, which can be considered to be similar as for wind turbine generators due the variability of primary energy supply and the range of grid coupling converters.

4.1.4 Voltage control ability of combined heat and power and combined heat, cold and power stations

In Europe more and more decentralized oriented combined heat and power (CHP) systems are applied to supply facilities with heat and the grid with electricity. For Brazil the concept of combined heat, cold and power (CHCP) generation might be more applicable.

Nevertheless, their ability to provide reactive power strongly depends on the grid coupling converter like with the other renewable generators discussed so far.

Large CHP and CHCP units in the megawatt range feed electricity via synchronous generators. For them the same reactive power characteristics are applicable as discussed in chapter 1.2.2 – "Reactive power provision by synchronous generators".

Smaller units for single buildings or group of buildings show variable grid coupling technology concepts – starting from pure induction generators with now reactive power control ability up to all other concepts that have been discussed with wind turbine generators.

4.1.5 Electricity storage facilities

Nowadays more or less the only electricity storage possibility applied in interconnected grids is pumped hydro power stations that are connected to the grid via synchronous generators. Therefore those storages are capable of providing reactive power.

In future with more (or even only) renewable energy devices currently a large variety of electricity storage possibilities are discussed. In the following a short overview is provided and evaluated according their reactive power provision capabilities.

<u>Batteries</u>. All batteries (lead-acid, lithium ion, redox flow, sodium sulfur, and many more) have in common that they provide direct currents and have to be connected to

the grid via inverters. For their reactive power provision capacity the same as mentioned for photovoltaic systems is valid.

Compressed air energy storage. Energy is stored in the form of compressed air. For reconversion to electricity the air is expanded in a gas turbine which drives a synchronous generator. For their reactive power provision capacity they have the same capabilities like other synchronous generator coupled power stations.

Flywheels. Flywheels can drive – like a turbine – synchronous generators. Therefore they again have the same abilities for the provision of reactive power like other synchronous generator coupled power stations.

Capacitors and superconductive coils. They store electricity directly. Nevertheless, they require a power electronic converter in order to provide grid compatible electricity. The same is valid as discussed for inverter coupled generators.

Hydrogen storage. Before hydrogen can be stored it is generated in an electrolyses process. Then it might be compressed and stored. Hydrogen can be reconverted into electricity by the mean of fuel cells. Fuel cells provide direct currents and have to be connected to the grid via inverters. For their reactive power provision capacity the same as mentioned for photovoltaic systems is valid.

4.1.6 Latest regulatory framework development in Germany

Chapter 4.1 described the possibilities of renewable energy systems to contribute to reactive power management and therefore to contribute to voltage and system stability. In May 2009 the German government released the „Act for the provision of anxiliary services by wind turbines" (Verordnung zu Systemdienstleistungen durch Windenergieanlagen) [AnxServiceAct 2009].

The content of this act is that wind turbines have to fulfill the same requirements for the management of reactive power than conventional power stations have to do. For the medium voltage gird these are the regulations according to "Mittelspannungsrichtlinie 2008". Among others that mean that wind turbines have to feed reactive power to the grid in case of a grid fault in order to stabilize voltage. When feeding to the high voltage grid wind turbines have to fulfill the "TransmissionCode 2007".

4.2 Frequency – active power control

As electricity cannot be stored in large magnitudes (except pumped hydro storages) electricity has to be generated in the moment of consumption. Imbalances between generation and consumption occur when forecasts of power consumption or generation from renewable generators are inaccurate. Another reason for imbalances is failures of power plants that have been planned to meet the actual power demand.

Generally there are two possibilities to react on deviations between generation and consumption. Firstly, the power generation can be adapted to the actual demand. Secondly, the power demand can be adapted to the actual power generation. Today's electricity supply systems use mainly the first possibility.

In chapter 1.2.2 it was explained that frequency is controlled by the provision of active power. To do so a certain control reserve has to be maintained that can be activated in case of imbalances within short times.

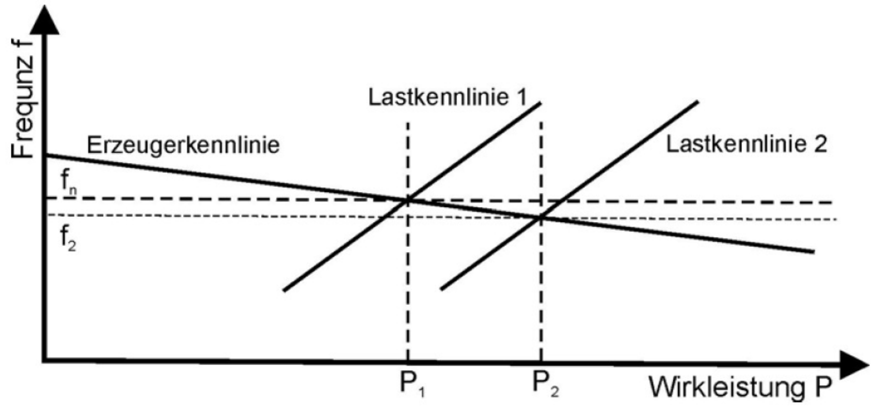
Base load power stations have high fixed costs and low variable cost. Therefore they are preferred to be operated in permanent operation. Peak-power power stations have low investment costs and higher variable costs and are used during short times. Mid-load power stations are in between of the other two categories.

Especially base-load power stations require a certain planning time before operated. That is due to required time to come into operation, minimum operation times and power gradients. For short time control flexible power stations are required. That is done nowadays with hydro power stations of the type “run-of-the-river” and “pumped hydro storage” and gas turbines. Additionally power stations are used that operate under part load conditions.

Responsibility for the provision of control power is allocated at the transmission grid operators. According to ENTSOE[2] (former UCTE) rules and the transmission code, respectively, deviations between generation and consumption are controlled with primary and secondary frequency control.

Primary frequency control

In case generation and consumption are balanced the operation point of the electricity system is in the intersection of the load characteristic (“Lastkennlinie”) and generation characteristic (“Erzeugerkennlinie”), see illustration 4.2.a. When the balance is disturbed a active power surplus or deficit occurs that is absorbed by the kinetic energy of the rotating generator masses. As a consequence frequency increases or decreases.



[2] European network of Transmission System Operators for Electricity

Illustration 4.2.a: Principle of primary control (frequency as a function of active power); (Translation: Frequenz = Frequency; Wirkleistung = Active Power; Erzeugerkennlinie = generation characteristic; Lastkennlinie = load characteristic)

In case of a positive load step that induces a frequency decrease the power stations react with an increase of active power generation. Different power stations can contribute in different ways to the primary control as is presented in illustration 4.2.b with the power station types A to E.

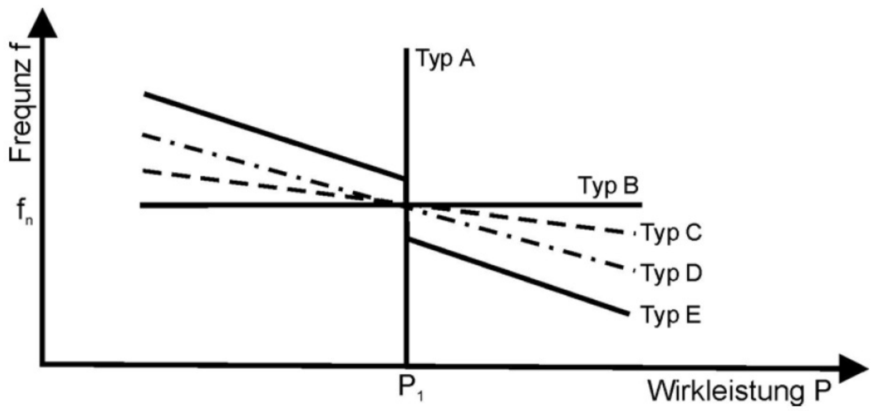


Illustration 4.2.b: different types of statics for different contributions of power stations to primary control (Translation: Frequenz = frequency; Wirkleistung = active power; Typ = Type)

The complete change in active power results from all speed controllers of all connected power stations within the interconnected electricity system. In contrast to voltage control frequency control is independent from the place of provision! These are decentralized measures for stability control of the interconnected network [Leonhard 1980].

Primary control stabilizes deviations from the grid frequency of its rated frequency within the ENTSOE grid within 30 seconds. For that purpose in the ENTSOE compound 3,000 MW of active power are held. That is the equivalent of two large steam power stations. Primary control has to be held for a period of 15 minutes.

With respect to renewable energies control power only has to be held for the deviation between active power generation and the actual active power provision. The forecast error is around 8 % for a day-ahead prognosis [ISET 2004]. [dena 2004] states that in the time range of primary control there is no additional need for primary control power caused by the integration of renewable energies.

With a very high fraction of renewable electricity generation technologies situations can occur where consumption is only a bit below or even equal to their respective active power generation. Keeping to nowadays strategies for primary control provision grid stability could not be guaranteed any more. This is because there is not any more sufficient conventional power generation capacity that provides primary active control power. As a consequence renewable power generators themselves have to

provide active control power or increased storage capacities have to be installed that could provide the control power. Another mean is a change in paradigm and control power will be provided by demand response [Stadler 2005].

Secondary frequency control

Only with primary control on the one hand an active power related frequency deviation would remain and on the other hand more or less large unintended power flows between different grid parts would remain. Because of that all grids are equipped with grid controllers that balance power flows with neighboring grids in a way that contractually agreed power flows are not exceeded. This is done in a way that generation characteristic “E1” in illustration 4.2.c intercepts power consumption characteristic “L1” at rated frequency. After the power consumption has increased to “L2” frequency “f_2” is obtained. The grid controller’s task is to shift the generation characteristic to “E2” and therefore rated frequency is achieved again.

It is in the responsibility of the transmission grid operator that in his control zone the active power is balanced. For that the grid operator has to hold sufficient secondary control power that can be activated within 5 to 15 minutes. With the help of the secondary control power grid frequency is brought back to rated frequency and power flows between control zones are brought back to agreed amounts.

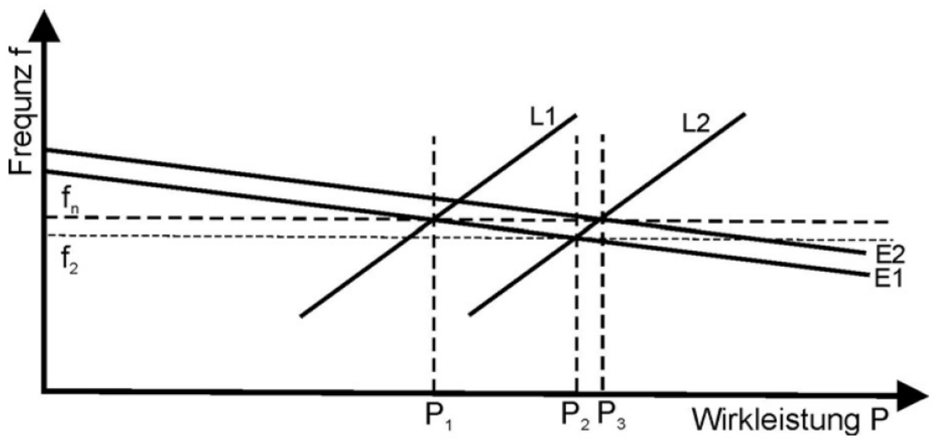


Illustration 4.2.c: Principle of secondary frequency control (Translation: Frequenz = frequency; Wirkleistung = active power)

4.2.1 Consequences in a changed electricity supply structure

Similar to chapter 4.1 the consequences can be discussed when due to a high penetration of renewable energies only few or in the extreme case no conventional power plant connected to the interconnected grid. How then frequency control can be supplied? Or can it be supplied by renewable energy or decentralized converters?

In contrast to reactive power supply that can be provided without active power generation (either by synchronous generators in phase shifting mode or inverters) without

active power generation frequency control is not possible. As a consequence not all renewable energy converters can contribute to frequency control all the time. E.g. during night photovoltaics cannot and during a calm wind turbine generators cannot contribute to frequency control.

But that does not mean that future electricity grids with mainly renewable power converters cannot anymore be operated stable. On the one hand the task of frequency control could be shared among different kinds of renewable power converters. On the other hand other facilities can take over the task more efficiently. These are electricity storages (among others electric vehicles) and demand response. They are discussed in brief in [Stadler 2005] but will not be discussed further here.

A grave argument that renewable generators should not participate in frequency control activities – at least not in positive frequency control – is that more or less all the cost of a renewable energy converter is investment cost and variable cost are close to zero. Therefore, economically it would be nonsense to operate a renewable energy converter all the year with a reduced capacity, only to supply “sometimes” a bit of positive active control power.

In the following the ability of some renewable energy converters to supply active control power is discussed.

Frequency control ability of wind turbines

An active power control is possible with all pitch controlled wind turbines independent from their grid coupling converter. The active power control changes are fast enough to fulfill the requirements of primary frequency control [Hartge et al 2005]. Even in case of critical situations for the voltage limits, active power of wind turbines can be changed fast enough to participate in primary voltage control, also in Fault-Ride Through situations.

Presently, wind turbine generators operate generally at the maximum available active power. In case of severe problems of network operation, network operators can limit the active power feed-in. This new maximum active power output value is reached within a couple of seconds. Moreover, a frequency dependant active power limitation can be applied to provide high frequency response.

Wind turbine generators with active power control reserve for low frequency control cannot operate at the maximum available or maximum allowed active power operation point. They have to operate below the maximum. Control algorithms are implemented therefore as described in [Abdad et al 2005], [Holdsworth et al 2004], [Prillwitz et al 2003] and [Prillwitz et al 2004].

At the maximum power coefficient, the maximum power from the available wind condition can be generated by the wind turbine generator. By varying the pitch angle and/or the tip speed ratio they are able to operate below the maximum to provide positive active power control. According to the studies in [Abdad et al 2005], both

strategies produce similar results but pitch variation has advantages in terms of stability, control capacity and control speed. As mentioned in the chapter before this operation mode is not a desirable one.

Frequency control ability of photovoltaic systems

A photovoltaic system has similar restrictions like a wind turbine generator with respect to primary energy variations. However, the characteristic of these fluctuations is different because at night there is no power generation. With appropriate forecast, a probabilistic use of active power control is possible, however, limited with respective uncertainties. The active power can be controlled by changing the DC-link voltage and moving on the VI-curve of the photovoltaic modules within milliseconds. Presently, photovoltaic systems use maximum power point (MPP) tracking to generate maximum active power.

Out of the same reasons that are given for frequency control with wind turbine generators also for photovoltaic systems this operation mode is not a desirable one.

Frequency control ability of run-of-the-river hydro power stations

Hydro power stations – and their provision of frequency control is standard all over the world and especially in Brazil. Therefore their ability is not discussed more detailed here.

Different from wind turbine generators and photovoltaic systems hydro power stations can operate below their actual maximum active power generation capability under certain circumstances – when they can store behind the dam.

Frequency control ability of combined heat and power and combined heat, cold and power stations

If combined heat and power systems or combined heat, cold and power systems, respectively, are capable to supply frequency or active power control the question is whether the system is either heat led or power led.

In case the system is heat led electricity production can be seen as a byproduct and the system is operated in order to match the heat demand of a certain facility. Only in combination with a heat storage electricity and heat (cold) generation can be decoupled. Then the CHP or CHCP system is capable to participate in frequency control. Illustration 4.2.1.a discusses the capability of a CHP unit with heat storage to provide control power that depends mainly on the storage size and the ambient temperature (in case the CHP is used to supply room heat).

In case the system is power led the heat can be seen as a byproduct. Therefore the system easily can participate in frequency control in the same way like nowadays power stations do. This is especially the case when the system is not a monovalent

but a bivalent one, which means that the system is equipped with second heat generator, e.g. a gas boiler system.

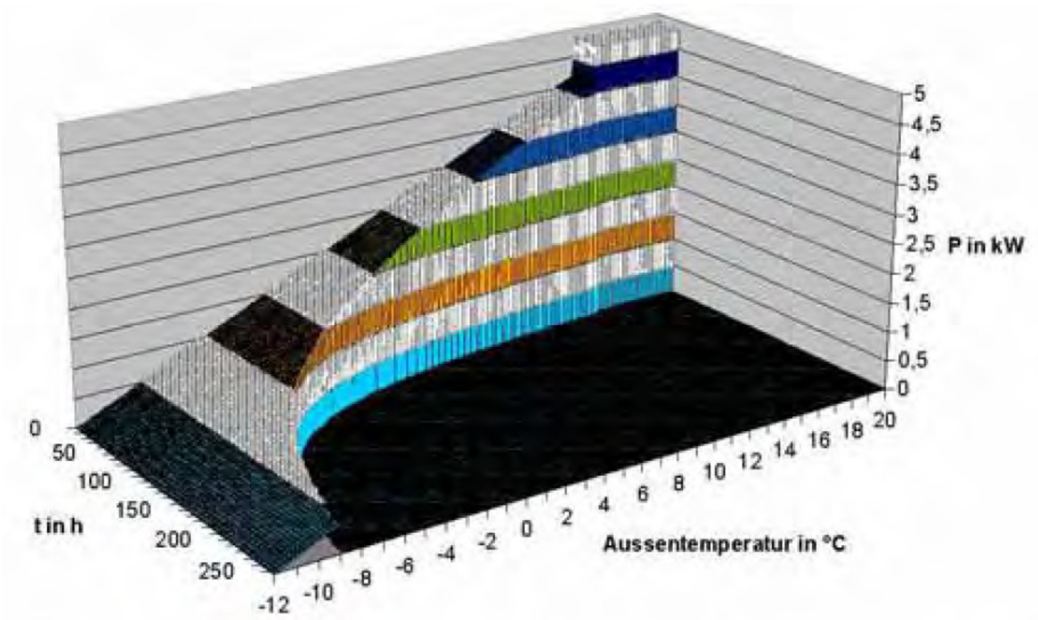


Illustration 4.2.1.a: Positive frequency control capability in terms of power and time availability of a monovalent CHP unit with heat storage depending on ambient temperature [Stadler 2005] (Translation: Aussentemperatur = ambient temperature)

4.3 Reduction of power losses

The main objective of the minimization of power losses is to reduce the costs of the power transmission and distribution due to transmission and distribution losses.
IEC 60287 provides a standard for the determination of line losses. The line losses P_L can be calculated with the equation:

$$P_L = P_L^{'} \cdot l = 3 \cdot R' \cdot I^2 \cdot l = 3 \cdot R' \cdot \left(\frac{S}{\sqrt{3}U}\right)^2 \cdot l = \frac{R' \cdot (P^2 + Q^2)}{U^2} \cdot l$$

The specific resistance *R'* and the length l is given by the line's characteristics and the current *I* is expressed by the active power flow *P* and the reactive power flow *Q* over the line with a voltage level *U*. This equation shows that the line losses are basically dependent on the:

- length of the line l
- resistance of the line R'
- active power flow over the line P
- reactive power flow over the line Q

- the voltage level of the line U.

Whilst the losses due to the resistance, the length and the voltage level can only be optimized during the network planning process, the losses due to active and reactive power flows can be optimized during the operation by power dispatch strategies.

As the reduction of power losses is directly linked to the provision of reactive power, for the ability of renewable energy sources to contribute to the reduction of power losses it is directly referred to chapter 4.1.

5 Regulations and standards concerning certification of electromagnetic compatibility and harmonic distortions of equipments and domestic appliances which are connected to the distribution grid

5.1 Introduction

Electromagnetic compatibility (EMC) means the ability of electrical or electronic equipment to function satisfactorily in its electromagnetic environment without introducing intolerable **electromagnetic interferences (EMI)** or disturbances to other equipment in that environment [EU 2004].

Sources of EMI are divided into several categories according to their signal characteristics. Sources of continuous narrowband interferences are for example all sorts of communication, radio, television or wireless local area network transmitters, high-frequency-generators in industrial or domestic environment, computer equipment or switching power supplies. Broadband transient interferences occur when the source emits a short-duration pulse of energy. Sources of such transient electromagnetic pulses are e.g. switching operations of electrical circuits (switching electromagnetic pulses, SEMP), electrostatic discharges (ESD) or lightning electromagnetic pulses (LEMP). Additionally there exist sources of repetitive electromagnetic pulses, like electric motors, ignition systems of engines, gas discharge lamps or high voltage overhead lines [Schlabbach 2008].

The electromagnetic interference between the source and the interfered or disturbed device ("sink") could be coupled on different ways. There exist four basic coupling mechanisms:

Conductive coupling occurs when the coupling path between the source and the sink is formed by direct contact with a conducting body, for example a transmission line, wire or cable. Capacitive and inductive coupling describes the coupling of electric and magnetic fields over short distances between conductors of source and sink, whereas radiative coupling occurs when the source radiates an electromagnetic wave propagating over a large distance. The sink is disturbed by the received electromagnetic field [Schwab 2007].

The goal of EMC is the correct operation of very different equipment in the same electromagnetic environment avoiding any interference effect. In order to achieve this, on the one hand the unwanted emission of electromagnetic energy by some source has to be reduced (active EMC). On the other hand the device has to operate correctly up to a certain amount of electromagnetic disturbances, which means the device should have a high immunity or low **susceptibility** (passive EMC). As it is in many cases not economic to reduce the unwanted emission of sources as far as technically possible or to optimize the immunity of devices, so-called **compatibility levels** were defined. Compatibility levels are accepted levels of disturbances, which are not exceeded in a specified system, e.g. the low-voltage grid, with a probability of typically 95% [Schwab 2007]. If the maximum emission of a device and its susceptibility is properly adjusted in dependence of the compatibility level, the device operates correctly in this system and other equipment connected to the system are not disturbed.

In the frame of this report concerning reactive power, power factor and also power quality (means voltage quality) the most interesting parts of EMC are electromagnetic interferences causing harmonics, inter-harmonics, flicker, changes or fluctuations of the supply voltage. These interferences are generated by industrial or domestic appliances, which are connected to the distribution grid, and are summarized under the term “**mains feedback**”. As the main coupling path of these interferences is simply the connecting line between the appliance and the grid, the main coupling mechanism in these cases is inductive coupling.

In the following a short overview of the general EMC standards and especially the standards concerning mains feedback is given.

5.2 Overview of EMC standards

The basis of all regulations and standards concerning electromagnetic compatibility (EMC) of any electrical equipment in Europe is the EMC Directive 2004/108/EC, which has been published in the Official Journal of the European Union, L 390/24, 31 December 2004, and repealed the old EMC Directive 89/336/EEC as from 20 July 2007. Referring to Article 15 of the EMC Directive 2004/108/EC it was possible to place an unchanged product on the market further on until 20th of July 2009, if it fulfils the essential requirements of the Directive 89/336/EEC and the first item was placed on the market before 20th of July 2007. After this transition period the EMC Directive 2004/108/EC is now binding within the EU for almost all electrical equipment [EU 2004].

Electrical apparatus or components intended to end-users must fulfill the essential requirements of the EMC Directive, which is shown by ‘CE’ marking of the product. The affixing of the ‘CE’ marking is the responsibility of the manufacturer or his authorized representative in the European Community [EU 2004].

Fixed installations, which are assembled at the site of operation, have to meet the EMC Directive, too. But they do not require a declaration of conformity, a ‘CE’ marking nor an approval of any competent authority [Gremmel 2006].

On the basis of the EMC Directive technical standards are developed for the European Union by the European Committee for Electrotechnical Standardization (CENELEC - Comité Européen de Normalisation Électrotechnique) resulting in so-called EN-standards . CENELEC works in close cooperation with the International Electrotechnical Commission (IEC) and the special international committee on radio interference (CISPR - Comité International Spécial des Perturbations Radioélectriques), so that most of the standards are international harmonized. In detail the following mapping between European and international standards is valid [Schlabbach 2008, Kampet 2007]:

- EN 6…. - European standard formed by using the IEC standard with the same number word by word
- EN 55… - European standard taken over from a CISPR standard
- EN 50… - European standard without international equivalent

In the field of electromagnetic compatibility there exist three general types of standards [Schlabbach 2008]:

- **Basic standards**: They relate to the general and fundamental rules to meet the necessary requirements. In addition to the classification of electromagnetic environments, they describe phenomena, terminology, compatibility levels and procedures of tests and measurements. The basic standards give recommendations for binding limits and requirements, too.
- **Generic standards**: The generic EMC standards define the minimum requirements and limits that equipment in a particular environment must meet. Concerning the environment it is distinguished between domestic area and industrial area. The generic EMC standards have to be applied if no product specific standards exist.
- **Product standards**: These standards define special limits and requirements for certain products and product families in combination with specific environmental conditions. The product standards take precedence over the generic standards.

In the following table some important EMC standards are summarized [Schwab 2007, Schlabbach 2008]:

Basic standards		
Measuring apparatus	EN 55016-1-X	Emission and Immunity
Measuring methods	EN 55016-2-X	Emission

	EN 61000-4-1	Immunity
Immunity tests	EN 61000-4-2 EN 61000-4-3 EN 61000-4-4 EN 61000-4-5 EN 61000-4-6 EN 61000-4-7 EN 61000-4-8 EN 61000-4-9 EN 61000-4-11 EN 61000-4-15 EN 61000-4-30	Electrostatic discharge (ESD) Radiated, radio-frequency, electro-magnetic fields Electrical fast transient (burst) Surge Conducted disturbances, induced by radio-frequency fields Harmonics and inter-harmonics Power frequency magnetic field Pulse magnetic field Voltage dips, short-term interruptions and voltage fluctuations Flicker Power quality
Compatibility levels for low-frequency conducted disturbances	EN 61000-2-2 EN 61000-2-4 EN 61000-2-12	Low-voltage power supply system Industrial plant Medium voltage power supply system
Limits of emission of harmonics and inter-harmonics	EN 61000-3-2 EN 61000-3-12	Equipment input current ≤ 16 A/phase Equipment input current ≤ 75 A/phase
Limits of emission of flicker, voltage changes and voltage fluctuations	EN 61000-3-3 EN 61000-3-11	Equipment input current ≤ 16 A/phase Equipment input current ≤ 75 A/phase
Generic standards		
Immunity	EN 61000-6-1 EN 61000-6-2	Domestic environments Industrial environments
Emission	EN 61000-6-3 EN 61000-6-4	Domestic environments Industrial environments
Product standards		
Emission and Immunity	EN 55011 EN 55022	Industrial, scientific and medical (ISM) devices Information and telecommunication equipment (ITE)
	EN 61800-3	Electric drives
	EN 50370-1/-2	Machine tools

The standards marked in blue are important for the mains feedback and some of them will be discussed more in detail in the frame of the next chapters.

5.3 Classification of mains feedbacks

Mains feedbacks (or “feedbacks to the grid” or “mains perturbations”) occur in the frequency range from nearly 0 Hz to roughly 10 kHz. They are caused by electrical equipment with non-linear current-voltage-characteristic connected to an electric power grid with finite short-circuit power, which means with an impedance greater than zero. The basic types of mains feedbacks are defined as follows [Schlabbach 2008]:

- **Harmonics** are sinusoidal voltage oscillations, which frequencies are integral multiples of the power frequency.
- **Inter-harmonics** are sinusoidal voltage oscillations, which frequencies are not integral multiples of the power frequency, which means that their frequencies are between the frequencies of the harmonics
- **Voltage fluctuations and flicker** – Voltage fluctuations are changes of the amplitude or rms-value of the voltage. They disturb the operation of sensitive devices and lead to so-called flicker, which is the subjective impression of fluctuations of the brightness of light bulbs or fluorescent lamps.
- **Voltage imbalances** as actual situation of the three-phase power system, where the rms-values of the three phase voltages are different or the angles between subsequent phases are not equal.
- **Frequency fluctuations** – changes of the power frequency (50 Hz)

Additional phenomena are described in the IEC 61000-2-1:

- **Short supply interruptions and voltage dips** describe the breakdown of the supply voltage for a time period of maximum 1 minute.
- **D.c. component**, which means the constant component of current or voltage (in discussion by IEC)
- **Mains signaling** are transfer signals of ripple controls on the electrical distribution grid.

In the frame of this study the power quality in general (chapter 5.4) and the occurrence of harmonics and inter-harmonics and measures to prevent them (chapter 5.5) are discussed more in detail.

5.4 Power quality following EN 50160

Power quality (means voltage quality) is defined by the European standard EN 50160. This standard describes the essential characteristics of the voltage in public low voltage and medium voltage grids at the hand-over or connection point. But

this standard specifies no limits concerning EMC, no compatibility levels or limits of emission. The standard EN 50160 describes only the range of different voltage characteristics, which are usually expected.

In the following some of these characteristics are given with their expectable value range for a low-voltage-grid with rated voltage of U_n = 230 V [Schlabbach 2008, EN 50160].

Characteristic	**Value range**
Frequency	50 Hz ± 1% during 95% of a week 50 Hz + 4% - 6% during 100 % of a week
Slow voltage fluctuation (10 min average time)	$U_{eff} = U_n \pm$ 10% for 95% of measured values
Fast voltage fluctuation (10 ms average time)	$\Delta u \leq$ 5%, up to 10% several times a day
Long-term flicker (2 h average time)	Flicker amplitude $P_{lt} \leq 1$ for 95% of a week
Voltage dip < 1 s	$\Delta u \leq$ 40%, 10 to 1000 times per year
Short supply interruption (< 3 min)	10 to 500 per year, 70% shorter than 1 s
Long supply interruption (> 3 min)	10 to 50 per year

(The flicker amplitude P_{lt} is measured and evaluated with a special algorithm described in EN 61000-4-30 [Mombauer 2006])

Following EN 50160 for harmonics with order ν the following values given relatively to the rated voltage, should not exceeded in 95% of the time:

ν odd, no multiple of 3		**ν odd, multiple of 3**		**ν even**	
ν	U_ν/U_n in %	ν	U_ν/U_n in %	ν	U_ν/U_n in %
5	6.0	3	5.0	2	2.0
7	5.0	9	1.5	4	1.0
11	3.5	15	0.5	6 … 24	0.5
13	3.0	21	0.5		
17	2.0				
19, 23, 25	1.5				
Total harmonic distortion value up to order 40: $THD_U \leq 8\%$					

For the definition of harmonics and of the total harmonic distortion value THD please see chapter 5.5.1.

5.5 Harmonics and inter-harmonics

Harmonics and inter-harmonics are caused in generally by non-linear loads or generators, like transformers, synchronous generators or fluorescents lights with conventional ballast. Additionally electrical equipment with power electronics, like rectifiers, triacs or thyristors, lead to high emission of harmonics. Power electronics are used in nearly all electronic devices, like personal computers, consumer electronics or compact fluorescent lights, as simple rectifiers, converter or in switching power supplies. In the year 2006 roughly 33% of the domestic appliances were electronic loads leading to a total system load of 9% or roughly 7 GW [Schlabbach 2008]. It is expected that the share of electronic loads will rise up in future because of the need to increase the energy efficiency.

Harmonics and inter-harmonics are also produced by power electronics used as converter for decentralized power generators, like wind turbines or photovoltaic systems.

5.5.1 Description of harmonics

In the case that voltage and current are periodical but not sinusoidal, because the fundamental oscillation is superimposed by harmonics, voltage and current can be expressed as sum of sinusoidal oscillations of different frequencies as follows:

$$u(t)=\sum_{\nu=1}^{H}\sqrt{2}\,U_\nu\cos\left(\nu\omega_1 t+\varphi_{U,\nu}\right)\qquad\text{and}\qquad i(t)=\sum_{\nu=1}^{H}\sqrt{2}\,I_\nu\cos\left(\nu\omega_1 t+\varphi_{I,\nu}\right)$$

The fundamental oscillations with the power frequency ω_1 is given for $\nu=1$, the harmonics for $\nu>1$. U_ν and I_ν are the rms values, $\varphi_{U,\nu}$ and $\varphi_{I,\nu}$ the phase shifts of the respective voltage or current oscillation. Calculating the total apparent power S of this system leads to the following result [Schlabbach 2008]:

$$S^2=P^2+Q_1^2+Q_d^2$$

P describes the total active power as sum of the active power of the fundamental oscillation of power frequency ω_1 and the active power of the harmonics with frequencies $\nu\omega_1$. The second term Q_1 describes the well-known reactive power of the fundamental oscillation (compare chapter 1). The third term Q_d is an additional part of reactive power resulting from the occurrence of the harmonics, called **distortion power**.

The **power factor** λ is now defined by the quotient of active and apparent power:

$$\lambda=\frac{P}{S}=\frac{P}{\sqrt{P^2+Q_1^2+Q_d^2}}$$

The interrelation between the different powers is shown in illustration 5.5.1.a.

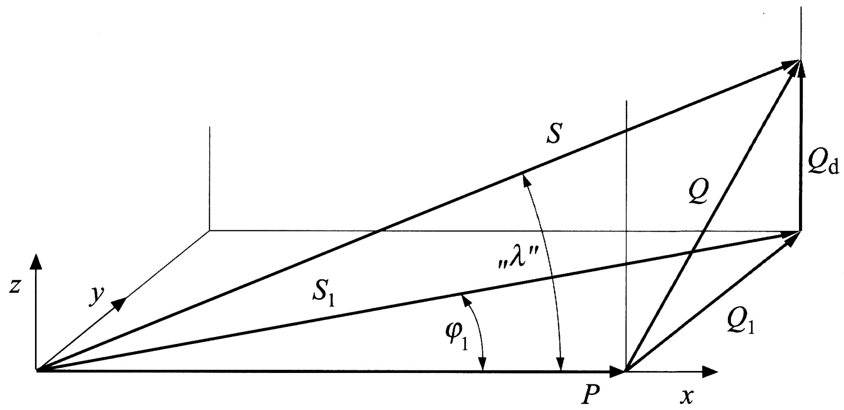


Illustration 5.5.1.a: Apparent, active, reactive, distortion power and power factor [Schlabbach 2008]

To evaluate the ratio of superimposed harmonics the so-called **total harmonic distortion (THD) value** is used, which is defined for voltage and current [Schlabbach 2008, DIN 40110]:

$$THD_U = \sqrt{\sum_{\nu=2}^{H} \left(\frac{U_\nu}{U_1} \right)^2} \qquad \text{and} \qquad THD_I = \sqrt{\sum_{\nu=2}^{H} \left(\frac{I_\nu}{I_1} \right)^2}$$

In the case of mains feedbacks the sums are only derived up to an order of $H = 40$ or $H = 50$.

As shown the power factor λ is different from the phase shift factor $\cos\varphi_1$ between voltage and current of the fundamental oscillation and decreases with the amount of harmonics. In the case of a nearly sinusoidal voltage (means $THD_U \approx 0$), the ratio between λ and $\cos\varphi_1$ is given as follows [Schneider 2007]:

$$\frac{\lambda}{\cos\varphi_1} = \frac{1}{\sqrt{1+THD_I}}$$

The ratio is shown in illustration 5.5.1.b in dependence on the total harmonic distortion current value THD_I. In any case of occurring current harmonics the real power factor λ is smaller than the phase shift factor $\cos\varphi_1$.

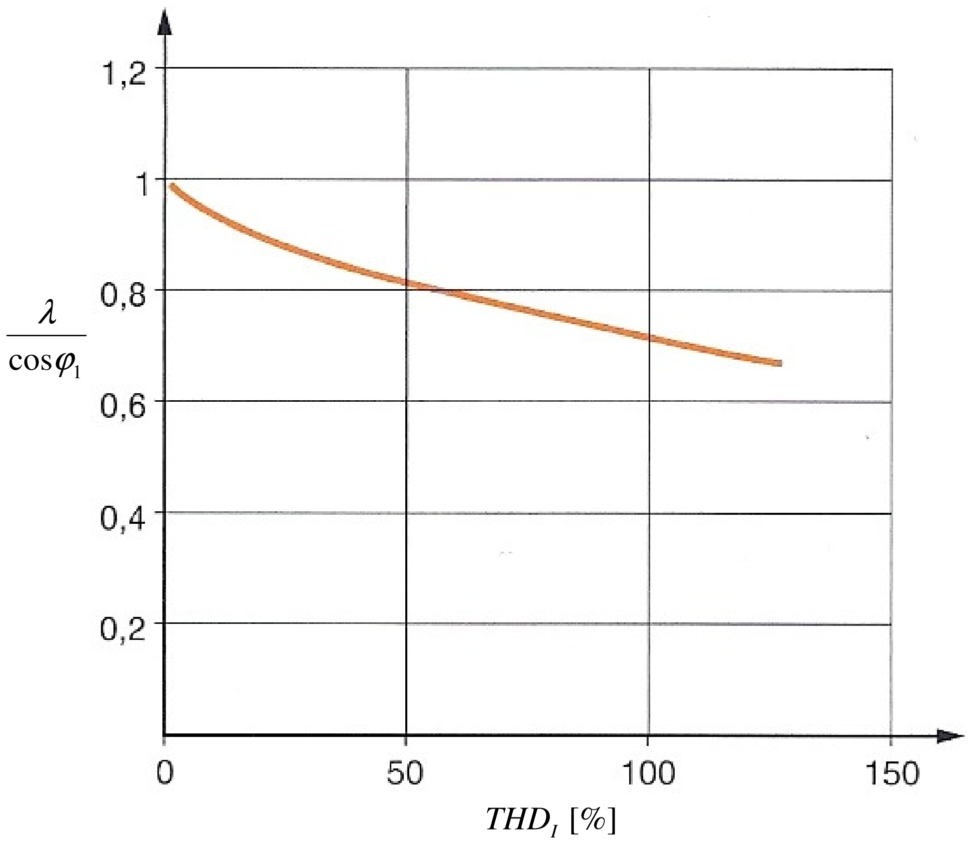


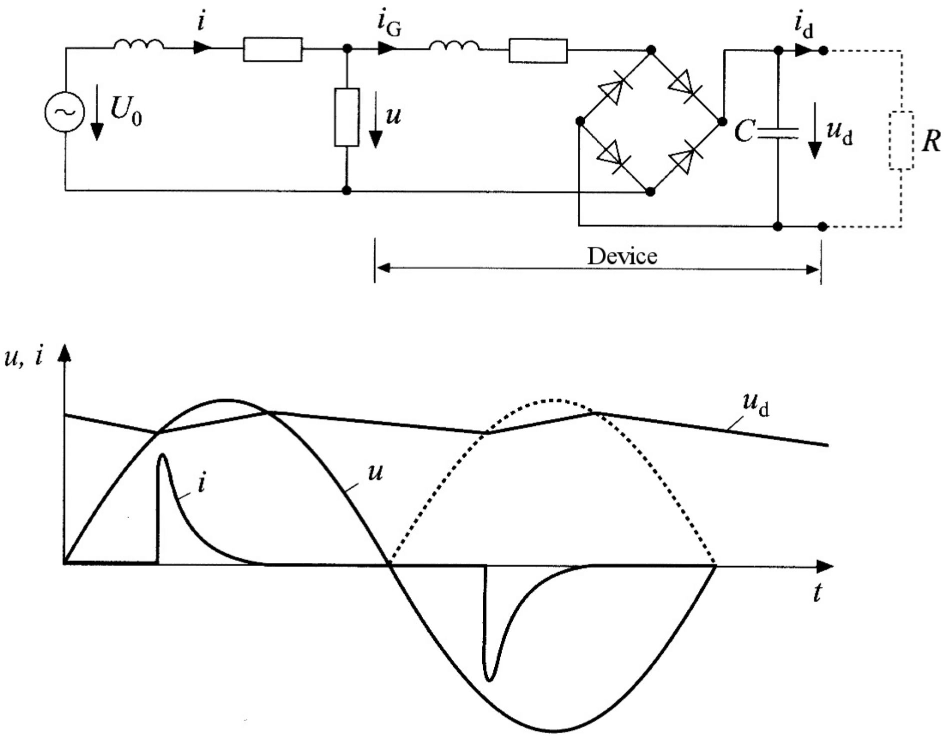
Illustration 5.5.1.b: Ratio between λ and $\cos\varphi_1$ in dependence on the total harmonic distortion current value THD_I for $THD_U \approx 0$ [Schneider 2007]

5.5.2 Main sources of harmonics and inter-harmonics

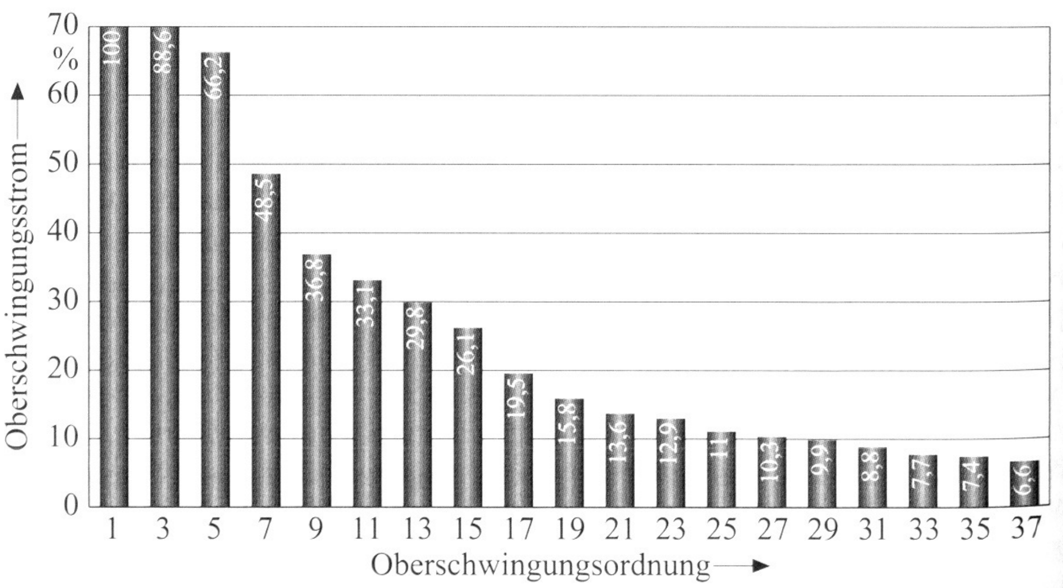
Bridge rectifier with capacitive smoothing

Most of the electronic devices connected to the distribution grid are using simple power electronics identical or comparable with a bridge rectifier with capacitive smoothing. Because the capacitor is only charged during a relative short time (typically 2 ms, see illustration 5.5.2.a), the power supply is loaded by a pulsed current resulting in high rates of harmonics. Harmonics with even order or inter-harmonics are not produced by bridge rectifiers.

As example the measured current harmonics of a primary switching power supply with capacitive smoothing are shown in illustration 5.5.2.b. The even orders of the current harmonics are negligible, but the odd orders play a significant role. The rms-values of the first three odd current harmonics with orders $\nu = 3, 5, 7$ are reaching values of I_3/I_1 = 88.6%, I_5/I_1 = 66.1% and I_7/I_1 = 48.5% (I_1 is the rms-value of the current of the fundamental oscillation).



Illustrations 5.5.2.a: Circuit diagram and voltages and current of a bridge rectifier with capacitive smoothing [Schlabbach 2008]



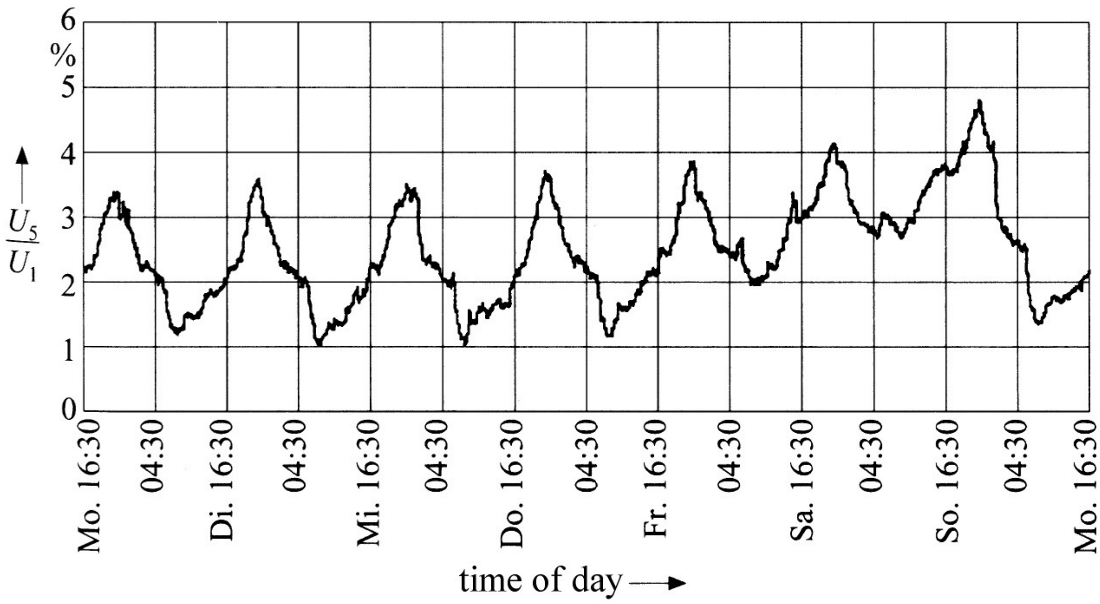
Illustrations 5.5.2.b: Relative Rms-values of the current harmonics ("Oberschwingungsstrom") in dependence of the order ν ("Oberschwingungsordnung") of a primary switching power supply with capacitive smoothing [Schlabbach 2008]

Due to the grid impedance current harmonics lead to voltage harmonics, which are able to disturb other electrical equipment connected to the grid. Harmonics in the low voltage grid and even in the medium voltage grid are mainly caused by bridge rectifiers with capacitive smoothing or similar power electronics, which are widely used for consumer electronics but also for washing machines, air conditioning units and com-

pact fluorescent lights with electronic ballast. The total effect of all electronic loads connected to the low voltage grid on the voltage quality is significant because of

- wide distribution of electronic devices with similar voltage-current-characteristic,
- in-phase operation of the devices, so that the pulsed currents are positive superimposed and
- synchronism of use of devices like TV sets or lightning especially in the evening or at the weekend.

Parts of the harmonics generated within the low voltage grid spread out into the medium voltage grid. Especially the 5th harmonic is dominating, when medium voltage grids supply residential areas. The 3rd harmonic is damped by the medium voltage transformers (connection Dy or Dz) because of their high zero-sequence impedance. Illustration 5.5.2.c shows the chronological sequence over one week of the relative rms-value of the 5th harmonics in a 10 kV medium voltage grid. Maxima of the 5th harmonic are visible in the evening times between 20 and 21 o'clock of each day. Additionally the value is generally increased at the weekend with additional small maxima at the afternoons. This distribution of the 5th harmonics can be traced back to the use of TV sets and other consumer electronics.



Illustrations 5.5.2.c: Relative rms-value of the 5th voltage harmonic in dependence of the time during one week in summer time for a 10 kV medium voltage grid in resistance area with a system load of 8.7 MW [Schlabbach 2008]

Line-commutating inverters

Line-commutating inverters need during operation a countervoltage and reactive power for their commutation. The generated harmonics depends only on the design of the inverter and the gate drive. Inter-harmonics are usually not generated.

A three-phase bridge using thyristors is a typical line-commutating inverter used e.g. in the frame of high-voltage direct current (HVDC) transmission. Depending on the number p of pulses of the inverter, the following harmonics are generated [Blume 1999]:

$$\nu = n \cdot p \pm 1 \quad \text{with} \quad n = 1, 2, 3, \ldots$$

The maximum rms-values of the current harmonics are given approximately by [Blume 1999]:

$$I_\nu \approx \frac{I_1}{\nu} \quad \text{with} \quad I_1 = \frac{\sqrt{6}}{\pi} \cdot I_d$$

I_d is the direct current on the load side. This means that a 6-pulse inverter generates harmonics of orders $\nu = 5, 7, 11, 13, \ldots$, whereas with a 12-pulse inverter only harmonics of orders $\nu = 11, 13, 23, 25, \ldots$ occur.

Self-commutating inverters

Self-commutating inverters have in general a smaller influence on the power quality. Because it is possible to control the used rectifiers (e.g. IGBTs) and to switch them off before natural current zero, the number of pulses can be increased by increasing the switching frequency resulting in reduced harmonics of low orders. Additionally the emission of distortions can be reduced by appropriate control methods depending on the load of the inverter.

But using a self-commutating inverter as frequency converter between the power grid and an electrical machine (motor or generator) also inter-harmonics with frequency f_j are produced in dependence of the frequency f_L of the machine-side [Schlabbach 2008]:

$$f_j = 2 \cdot m \cdot q \cdot f_L \quad \text{with} \quad m = 0, 1, 2, 3, \ldots$$

q is the number of windings of the connected machine. In combination with the harmonics the following frequencies of distortion currents are possible (f_N is the frequency of the power grid):

$$f = (n \cdot p \pm 1) \cdot f_N \pm 2 \cdot m \cdot q \cdot f_L$$

5.5.3 Impact of harmonics and inter-harmonics

In general electrical devices with high capacitance, like cables or capacitors for reactive power compensation, are especially endangered by harmonics and inter-harmonics. Because the impact of harmonics and inter-harmonics on capacitors is in principle the same, inter-harmonics are not mentioned in the following and the term “harmonics” is used for both.

Illustration 5.5.3.a shows a typical grid configuration: A high voltage grid feeds over a transformer T a medium voltage cable grid. An inverter, its compensation capacitor C_K and a load is connected to the medium voltage grid. From the point of view of the inverter as source of current harmonics, the compensation capacitor C_K, the cable capacitance C_b and the inductance L_{kT} of the transformer are in parallel forming a parallel resonance circuit (see illustration 5.5.3.b, left) [Heuck 2007]. The influence of the load is neglected in the following.

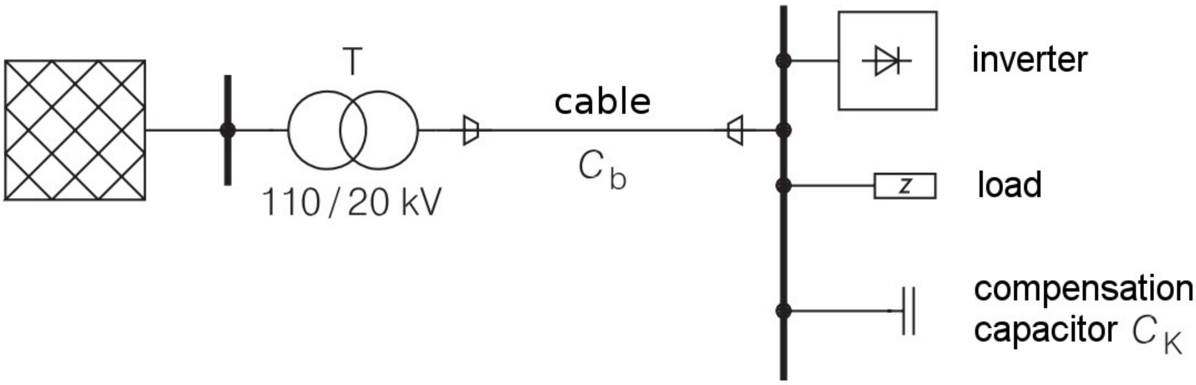


Illustration 5.5.3.a: Typical grid configuration [Heuck 2007]

The resonance frequency of the parallel resonance circuit is given by

$$f_{res} = \frac{1}{2\pi\sqrt{L_{KT} \cdot (C_K + C_b)}}$$

Typical values of the resonance frequency are in the range of 200 Hz to 2 kHz, that means in the typical range of harmonic currents (order 4 to 40). For a harmonic current with a frequency near the resonance frequency of the system, the total impedance of the system is increased resulting in over-voltages possibly damaging the capacitor. Simultaneously a high current is flowing within the parallel resonance circuit between capacitance and inductance possibly leading to an overstress of the electrical equipment.

For this reason it is defined, that capacitors have to withstand a continuous current of 130% of the rated current and a continuous voltage of 110% of the rated voltage. Short-time voltages can be even higher up to 130% of the rated voltage [Heuck 2007, EN 60831].

If this over-dimensioning is not sufficient, a filter inductance L_F is used in series to the compensating capacitor (see illustration 5.5.3.b, left). The filter inductance is chosen in the way, that L_F and C_K are forming a series resonant circuit with the same resonance frequency f_{res} of the system. Now the impedance of the system is nearly zero for the frequency f_{res}, the “dangerous” harmonic is short-circuited (see illustration 5.5.3.b, right).

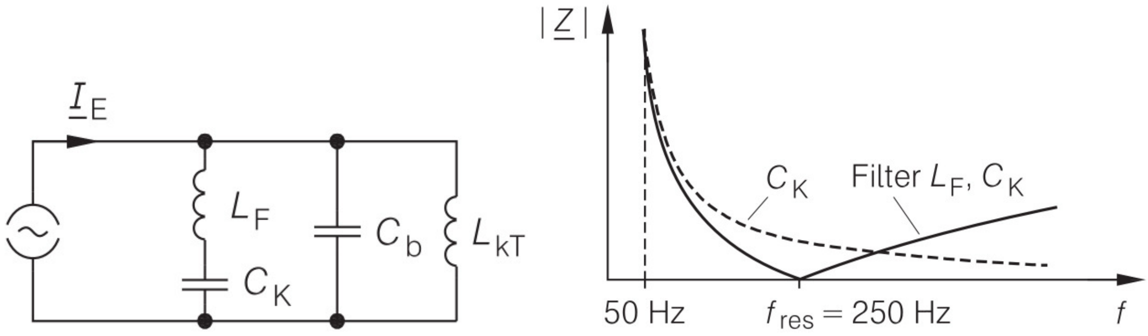


Illustration 5.5.3.b: Simplified equivalent circuit of the grid configuration in illustration 5.5.3.a (load and inductance of the cable neglected) with additional filter inductance L_F (left) and impedance of the series resonance circuit C_K, L_F in dependence of the frequency [Heuck 2007]

The function of the capacitor to compensate the reactive power at 50 Hz is not significant affected, as the filter inductance has only an influence on the total impedance at higher frequencies (see illustration 5.5.3.b, right).

As the needed reactive power compensation is load dependent, the capacitance has to be changed according to the load situation. In practice this is realized by capacitors in parallel switched on and off. But then the resonance frequency is also changing in dependence on the load situation, so that different harmonics can be dangerous for the capacitor bank. This can be solved by using filter impedances for each switchable capacitor, so that for each dangerous harmonic a filter circuit is available (see illustration 5.5.3.c).

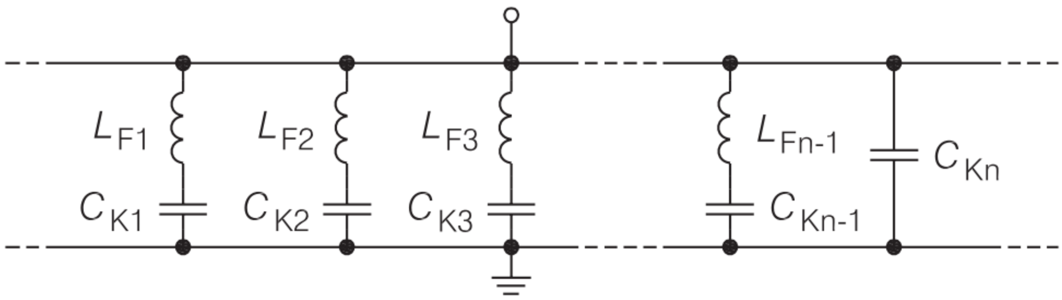


Illustration 5.5.3.c: Arrangement of a capacitive system for reactive power compensation with several filters of harmonics [Heuck 2007]

Further electrical equipment, like overhead lines, transformers, instrument transformers, electrical machines or electronic devices can be influenced by harmonics, too. For more information please see [Schlabbach 2008, Blume 1999].

5.5.4 Compatibility levels and limits of harmonics

Compatibility levels

Compatibility levels are accepted levels of disturbances, which are not exceeded in a specified system with a probability of 95%. For public low voltage and medium vol-

tage grids the compatibility levels for quasi-static (longer than 10 min lasting) harmonics are given in illustration 5.5.4.a, separated for even orders (a), odd orders, no multiple of 3 (b) and odd orders, multiple of 3 (c) (further values are defined up to the order 50 not shown illustration 5.5.4.a, please see [Schlabbach 2008, EN 61000-2-2, EN 61000-2-12]. The limit of the total harmonic distortion value THD_U up to order 50 is 8%.

To operate an electrical device in a public low voltage and medium voltage grid without EMC problems, one has to be sure, that the device is able to withstand the given amount of harmonics without damage or misoperation. In practice it is even necessary to have some margin, because with a probability of 5% the limits of the harmonics are exceeded.

Comparing the compatibility levels with the voltage characteristics given in EN 50160 (see chapter 5.4) makes clear, that the values are identical up to order 11. For higher orders up to 25 the values differ slightly from each other, while values for orders up to 50 are only defined as compatibility levels. Please consider in this context that the values in EN 50160 are only typical values, while the compatibility levels are basis for dimensioning the EMC of electrical devices.

For short-time harmonics (< 10 min) the compatibility levels are increased by a factor k, which is defined in dependence of the order ν as follows:

$$k = 1.3 + \frac{0.7}{45} \cdot (\nu - 5)$$

The corresponding total harmonic distortion level THD_U up to the order 50 is increased to 11% in the case of short-time harmonics.

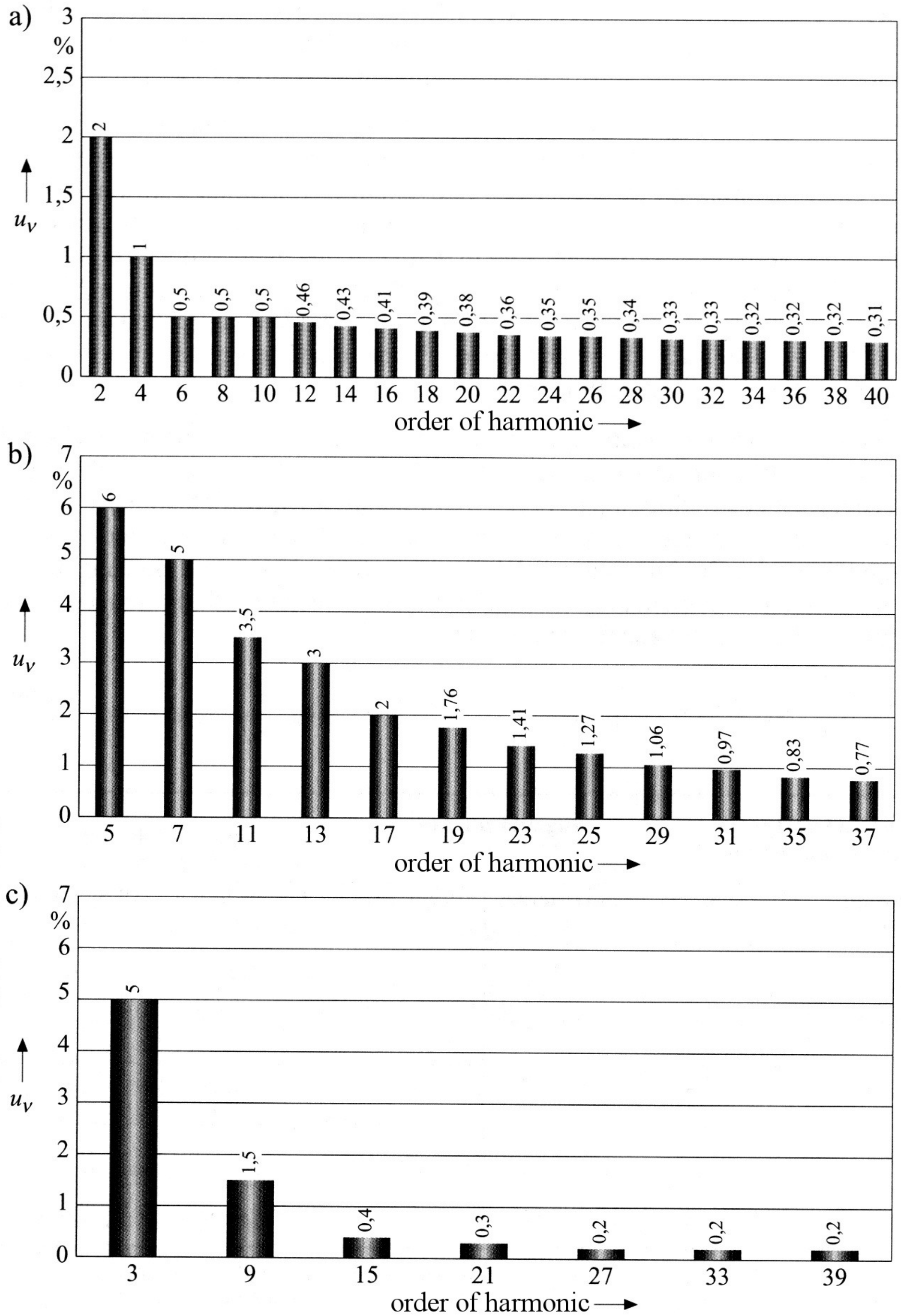


Illustration 5.5.4.a: Compatibility levels of voltage harmonics in public low voltage and medium voltage grids following EN 61000-2-2 and EN 61000-2-12, the values are rms-value of the harmonics given as proportion of the fundamental oscillation [Schlabbach 2008]

Compatibility levels are also defined for industrial grids following EN 61000-2-4. In this frame there are three electromagnetic environment classes defined, given in the following together with the defined total harmonic distortion value of quasi-static harmonics:

- **Class 1** - THD_U = 5% - Protected supply for e.g. laboratories, electronic data processing, some protection and automation systems

- **Class 2** - THD_U = 8% - Connection point to the public grid, the compatibility levels are the same as for the public grid (see illustration 5.5.4.a)
- **Class 3** - THD_U = 10% - Internal supply terminal characterized by operation of welding machines, frequent start of electric motors, fast changing loads or loads with high amount of power electronics

Further information and detailed values of the individual harmonics can be found in [Schlabbach 2008, EN 61000-2-4].

Based on the compatibility levels, which should not exceeded in 95% of the time in low voltage and medium voltage grids, the maximum emission of current harmonics of electrical devices connected to the public low voltage grid with a rated current up to 16 A and between 16 A and 75 A are defined in EN 61000-3-2 and EN 61000-3-12, respectively.

Limits of harmonics for electrical devices with rated current up to 16 A

It is allowed to connect devices with a rated current up to 16 A per phase, which fulfills the requirement of EN 61000-3-2, at any connection point to the public low voltage grid without any further test. The standard is valid for

- domestic appliances, electric heating systems and cookers,
- TV sets, consumer electronics, computers,
- illumination equipment,
- fixed electric tools, portable electric tools for short-time operation and
- welding equipment for non-professional applications.

For the following devices no limits are defined:

- devices with rated power up to 75 W except for illumination equipment,
- professional devices with rated power > 1 kW,
- symmetrically controlled heating units up to 200 W and
- dimmer for light bulbs up to 1 kW.

The different effects of the devices on the power quality are considered by introducing different classes of equipment:

Class D: Computers and TV sets with a rated power up to 600 W

For this class the emission limits of harmonic current distortions are shown in illustration 5.5.4.b. For each odd harmonic two values are defined. On the one hand the maximum rms-current, which is identical with class A, and on the other hand the rms-current related to the power of the device. In any case the smaller value has to be kept. For even harmonics limits are not given, because switching power supplies produce in general no harmonics of even order. For equipment with rated power clearly smaller than 600 W, the limits are hardly to fulfill especially at low costs.

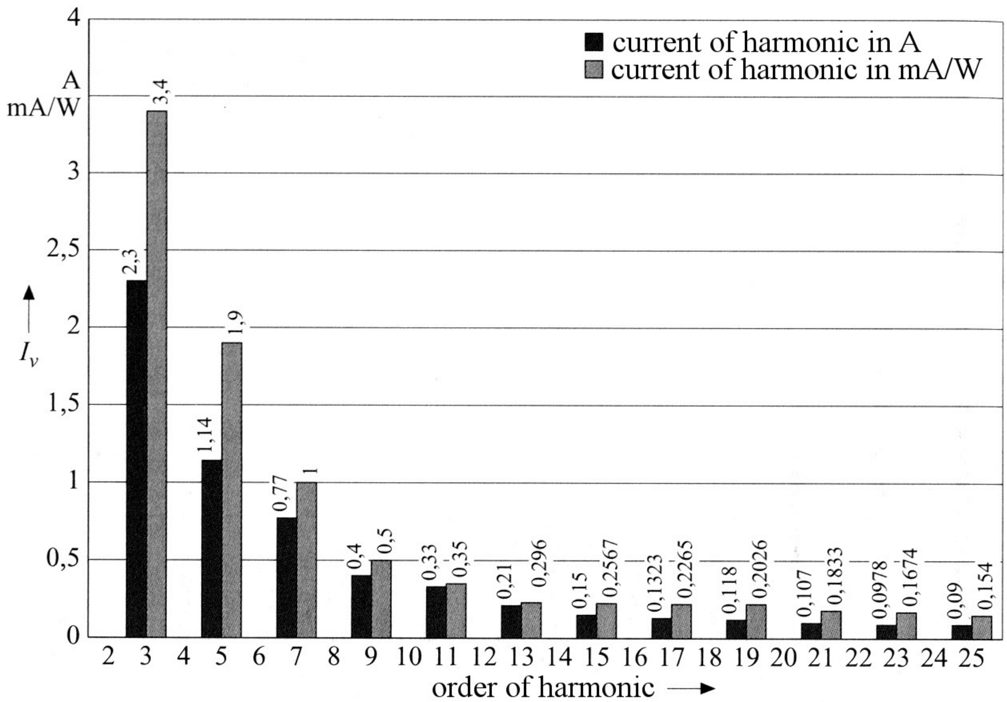


Illustration 5.5.4.b: Emission limits of harmonic current distortions for electrical devices with a rated current up to 16 A, class D, following EN 61000-3-2 [Schlabbach 2008]

Class C: Illumination equipment

Class C is valid for all illumination equipment even with rated power smaller than 75 W, which means that the limits shown in illustration 5.5.4.c has to be fulfilled by all compact fluorescent lights, too.

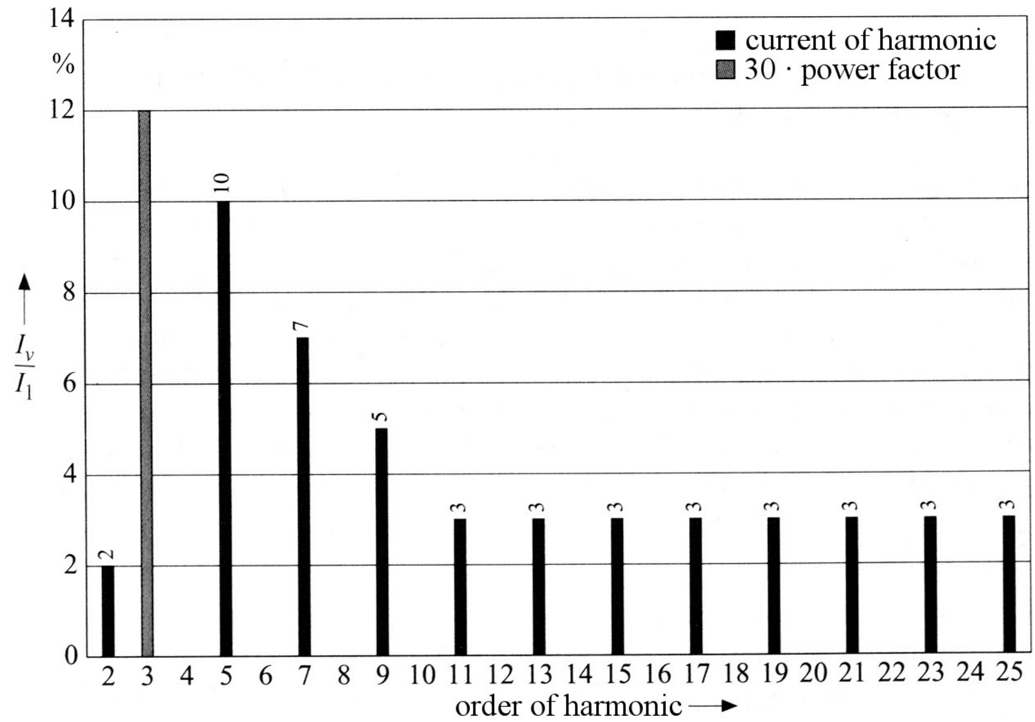


Illustration 5.5.4.c: Emission limits of harmonic current distortions for electrical devices with a rated current up to 16 A, class C, following EN 61000-3-2 [Schlabbach 2008]

Class B: Portable electric tools and non-professional equipment systems

This class includes only portable electric tools. As these tools are operating in practice only for short time, the emission of current harmonics can be higher than in class A. The limits are defined as 150% of the limits given for class A (see illustration 5.5.4.d)

Class A: All devices, which not belongs to the other classes

For all devices of the general class A the maximum emission of harmonic current distortions are given in illustration 5.5.4.d.

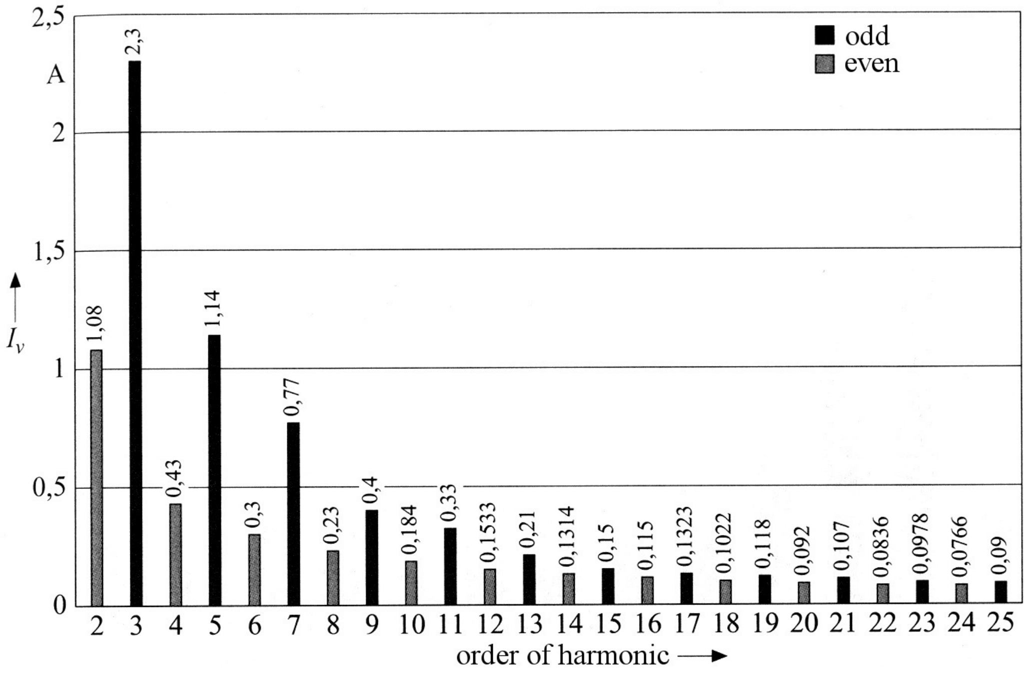


Illustration 5.5.4.d: Emission limits of harmonic current distortions for electrical devices with a rated current up to 16 A, class A, following EN 61000-3-2 [Schlabbach 2008]

Devices, which are not able to fulfill the limits of their class, can be operated only with a special permit of the grid operator.

Limits of harmonics for electrical devices with rated current 16 A to 75 A

For electrical devices with rated current higher than 16 A up to 75 A emission limits of harmonic current distortions are defined in EN 61000-3-12. The limits depends on the so-called **short-circuit ratio** R_{sc}, which is the quotient of the short-circuit-power S_k of the grid at the connection point and the power of the device S_D: $R_{sc} = S_k / S_D$. With increasing short-circuit ratio the emission of current harmonics has a decreasing influence on the voltage quality, because the generation of voltage harmonics is reduced. Therefore higher limits of current harmonics are allowed in the case of higher values of the short-circuit ration. Additionally one has to distinguish between devices, which are symmetric or unsymmetric concerning the three-phase-power consumption.

The dependence on the short-circuit ratio means that devices with rated current higher than 16 A can not be connected to the low voltage grid at any point. It is necessary to determine the short-circuit-power of the grid at the connection point. Additionally the compliance of the connected equipment with EN 61000-3-12 has to be verified by measurement or secured simulation.

Further information and detailed description of the limits are given in [Schlabbach 2008, EN 61000-3-12].

5.5.5 Measurement of power factor in the case of present harmonics

Conventional analog meters do not accurately measure the rms values of nonsinusoidal voltages and currents due to deficiencies in their response to higher frequency components. Therefore it is only possible to detect the phase shift factor $\cos \varphi_1$ between voltage and current of the fundamental oscillation and not the power factor if harmonics are present.

But with state-of-the-art electronic meters the measured values of current and voltage are digitized using high-precision A/D converters with a high sampling frequency of e.g. 2400 Hz. The digitized values are forwarded to a DSP (digital signal processor), which calculates the active, reactive and apparent power, the power factor and the needed energies (see chapter 3.1). These devices are able to measure power factor and phase shift factor and are able to determine the total harmonic distortion factor.

To analyze the frequency spectrum in detail harmonic analyzers are used. They are able to determine the wave shapes of voltage and current and to measure the respective frequency spectrum. These analyzers are typically used if problems with a two high amount of harmonics are supposed at some network connection point.

Reactive power compensation means are only able to compensate the reactive power of the fundamental oscillation. Therefore they are regulated in the grid in dependence on the phase shift factor $\cos \varphi_1$. To limit harmonics it is necessary to monitor the voltage quality, to identify electrical devices exceeding the emission limits and to use adequate filters of harmonics in combination with the compensating capacitors.

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